PRICE TEN SHILLINGS AND SIXPENCE

THE JOURNAL OF

The Institution of Electrical Engineers

ORIGINALLY

The Society of Telegraph Engineers

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY P. F. ROWELL, SECRETARY

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 81 AUGUST, 1937 No. 488

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E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

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[*Continued on page (III) of Cover.*

LAYOUT AND RUPTURING CAPACITY OF PROTECTIVE DEVICES IN MOTOR CIRCUITS

By J. O. KNOWLES, M.A., Associate Member

[*Paper first received* 13*th June, and in final form* 17*th November*, 1936; *read before* THE INSTITUTION 21*st January, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 18*th January, before the* NORTH-WESTERN CENTRE 2*nd February, before the* NORTHERN IRELAND SUB-CENTRE 16*th February, before the* IRISH CENTRE 18*th February, before the* NORTH-EASTERN CENTRE 22*nd February, before the* WESTERN CENTRE 22*nd March, and before the* TEES-SIDE SUB-CENTRE 20*th April*, 1937.]

SUMMARY

The paper deals with some of the practical considerations that will determine the decisions on technical points taken by engineers who are responsible for the installation of motor control gear and sub-distribution switchgear, for isolating and protecting motor circuits.

The functions of isolation and protection are shared by motor control gear and sub-distribution switchgear, especially when motors function in groups. Various grouping arrangements are compared.

The use of 3 300 volts in motor circuits is discussed, and a reference is made to the use of 3 300-volt contactors.

The increasing use of contactors emphasizes the importance of further study of the process of making and breaking circuit by means of contactors, which can be examined in more detail by a demonstration with slow-motion films.

After a note on thermal overload trips, the rupturing capacity of starters is discussed with particular reference to the short-circuit values which can be fed from the transformers and supply cables usual in l.t. circuits.

The rupturing capacities of rewireable and cartridge fuses are discussed, with particular reference to the time of operation of the latter on severe short-circuits.

The rupturing capacity of l.t. circuit breakers is shown to involve problems akin to those which have been studied in h.t. switchgear design.

Finally, the problem of the anticipation of short-circuits by leakage indication is stated in terms of practical application.

DISTRIBUTION LAYOUT FOR MOTOR CIRCUITS

The layout of distribution and starting switchgear for motor circuits provides opportunities for co-operation between engineers concerned with distribution switchgear and those concerned with starters. The primary function of the starter is certainly to start and stop the motor. Almost all starters are, however, provided with overload trips to protect the motor. This function of protecting the motor circuit is thus shared by the starter and the distribution switchgear, with the distinction that the starter is primarily intended to protect the motor from overload, and the distribution switchgear is primarily intended to protect the circuit from short-circuit conditions. Further, it is becoming more common to fit starters with interlocked isolating switches, for convenience in maintenance and to ensure full compliance with Home Office recommendations. The distribution switchgear also involves means of isolating each motor circuit.

The protecting and isolating functions of the starter should therefore be considered in conjunction with the protecting and isolating functions of the distribution switchgear. Some of the considerations involved are reviewed in this paper.*

* See Reference (1).

GROUPING AND ISOLATION OF MOTOR SWITCHGEAR

It is becoming more common to consider the control of motors in groups, rather than individually. Thus a number of motors driving conveyors or elevators may be started in sequence. A pumping installation may have several motors, some or all being used according to the flow of water. A machine tool may carry a number of motors driving different parts of the machine and controlled from a central position. For a boiler installation, some starters may be supplied by the fan makers, some by the stoker manufacturers, and some by other contractors, but they are all auxiliaries for the same installation, used and maintained by the same staff and fed from the same distribution switchgear.

In general, the user contracts separately for his distribution switchgear and his motor control gear. In the case of small extensions to existing plant, he orders the starters in conjunction with the ordering of the main plant, and extends his distribution switchgear to cope with the extra load and to provide the number of new sub-circuits required for the new plant. In some cases the main contractor for the new plant provides the motors and starters and the cables between motors and starters, leaving the user to wire up to the starters. In other cases the main contractor provides all that is necessary beyond the main incoming supply.

It is therefore difficult to deal with the layout of motor control gear and distribution gear for a group of motors in general terms, but the following are some types of layout which are becoming more common:—

(a) Multi-motor Panels

Where several motors are used on the same machine, it is obviously reasonable to include the control gear for all of them in the same case. Thus a woodworking machine may have several motors and the control gear for all these motors can be housed in a single cavity in the side of the machine (see Fig. 1A). Such layouts are designed by co-operation between the machine maker and the control-gear maker, and this co-operation is most effective where the machine maker employs a fully qualified electrical engineer.

On a large machine, the control gear may be built into a pillar standing by the side of the machine. A wheel lathe, for instance, may have a large motor for the main drive and several smaller motors for auxiliary motions, the control gear for all motors being built into one case with a single interlocked isolating switch cutting off the control gear for all motors from the incoming supply (see Fig. 1B). The supply is brought into the pillar

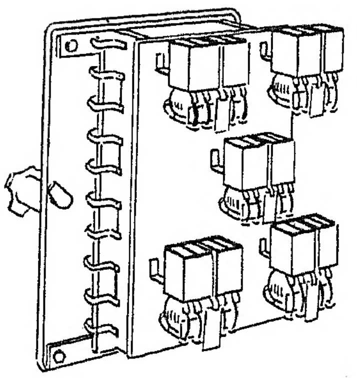

Fig. 1A.—Built-in control gear for several motors on woodworking machine.

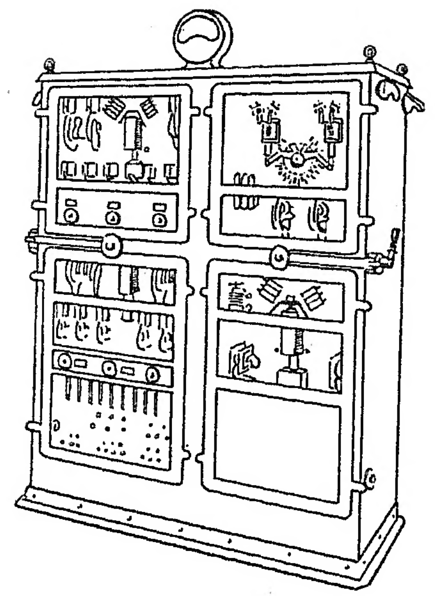

Fig. 1B.—Control gear for wheel lathe, controlling main motor and six auxiliary motors with common isolating switch.

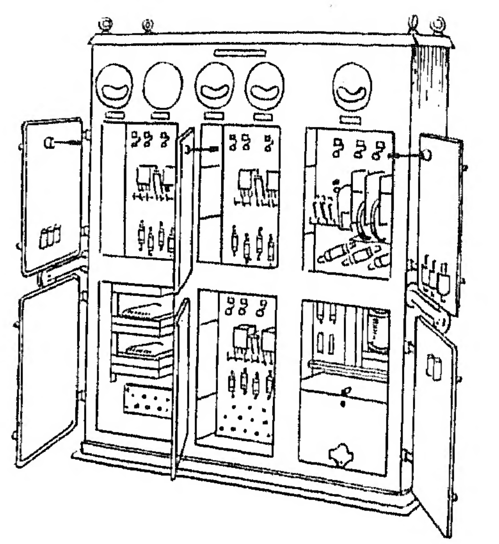

Fig. 1C.—Control gear, with common isolator, for four motors driving conveyors in sequence; provision is made for a future circuit.

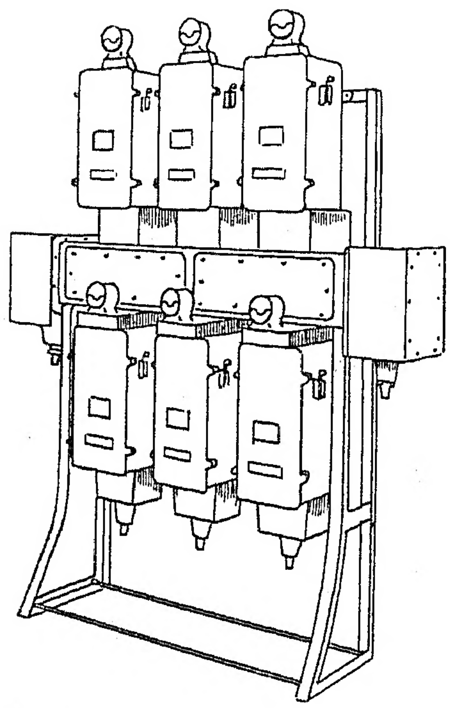

Fig. 1D.—Group of starters on common busbar chamber, each with isolator and high-rupturing-capacity fuses.

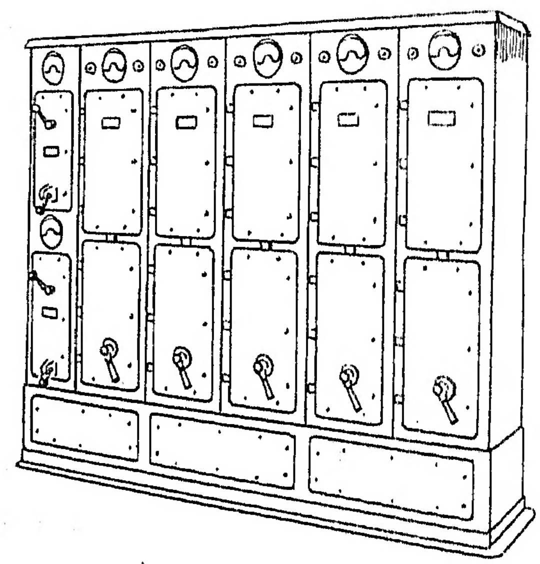

Fig. 1E.—Group of starters mounted in extensible ironclad switchboard form.

through an interlocked isolating switch, no further distribution or protective gear being required except at the supply end of the cable feeding the whole machine.

This principle of grouping the control gear for several motors can be extended to cover instances where the motors do not operate on the same machine, but on several machines in a definite sequence, such as a sequence of conveyors. Fig. 1C shows a control panel for a group of four conveyors, with provision for a future fifth circuit. A common isolating switch is interlocked with the doors of all the starters, since any attention to the control gear for one motor necessarily involves the stopping of the whole sequence.

(b) Grouped Starting Panels

Where a number of motors operate in the same room, but not necessarily on the same machine or in a definite sequence, a number of starters may be grouped on a common busbar chamber (see Fig. 1D). Each starter has an interlocked isolating switch, so that maintenance attention can be given at any time without shutting down other starters; and if the supply is capable of giving high short-circuit currents the overload protection of the motor can be supplemented by the use of high-rupturing-capacity fuses, easily accessible under the protection of the isolating switch.

The starters grouped in this way may either be mounted in separate cases above and below a busbar chamber or mounted in the form of an ironclad switchboard consisting of a number of pillar-type cases of equal height bolted together, as shown in Fig. 1E. This construction is a logical development from the open-type switchboard consisting of a number of slabs on a common framework, but with the additional advantages of separate enclosure and separate isolation of each unit. From the point of view of the maintenance engineer, the switchboard construction has a natural advantage in position as compared with the use of individual starters, which tend to be mounted in less accessible and less well-lighted positions.

It is not desirable to group starters where the motors are so scattered that the switchboard is out of sight of some of the motors. Means of isolating the supply from the motors should be provided within sight of the motor. If in a particular instance it is still considered desirable to group the starters, although some motors are out of sight, three alternatives are possible:—

(i) An emergency "stop" button or control switch should be placed near the motor. The stop button should be of a type which can be locked down, and the circuit should be such that the stop button breaks the main contactor coil circuit. Where the stop button has to make a shunt trip circuit or even where the stop button breaks the circuit of a no-volt trip which trips a mechanical latch, there is a chance that the shunt trip circuit will not be *made*, or that the starter or circuit breaker (even of the free-handle type) may be closed—in spite of the free-handle feature—owing to some mechanical stiffness or other similar reason.

(ii) A motor isolating switch may be mounted between the starting panel and the motor (close to the motor) which will definitely cut off the supply to the motor. This motor isolating switch, in addition to breaking all poles of the main supply, should have an auxiliary contact interlocked with the starter no-volt coil so that the starter and not the motor isolating switch must be used to restart the motor.

(iii) For those motors which are out of sight of the switchboard, switch-fuses can be mounted on the switchboard, feeding individual starters mounted close to their respective motors (Fig. 2 on Plate 1, facing page 152).

(c) Tee-off and Ring-main Layouts

Instead of using a central sub-circuit fuseboard with outgoing cables to each motor position, the supply may be tapped off at various points in a line of busbars carried overhead, with fuses for protection and isolation at each tee-off junction. This construction is particularly helpful when alterations of motor positions or the addition of other circuits becomes necessary. For other circuits, and particularly where the importance of the layout justifies the extra expense, a ring main may be laid out between groups of starting panels with isolating switches to cut out a faulty section or to provide an alternative supply (see Fig. 3 on Plate 1).

The above schemes are typical of layouts where the isolating and protective features of starters are considered in conjunction with the layout of distribution switchgear. They are alternative to the more usual layout of sub-circuit distribution boards and individual starters, and should be applied with discretion and with special reference to the conditions of the individual installation concerned.

USE OF 3 300 VOLTS IN MOTOR CIRCUITS

There is a tendency to increase the voltage of h.t. distribution networks from 6 600 volts to 11 000 volts. An overhead line with conductors designed to carry 100 amps. will carry about 1 000 kVA at 6 600 volts, but (with larger insulators) about 1 650 kVA at 11 000 volts. In dense areas of distribution also, the most common size of distribution circuit-breaker (300 amps., 6 600 volts, 150 000 kVA) becomes insufficient in carrying capacity and rupturing capacity. At 11 000 volts more power can be carried without exceeding 300 amps. for switches or outgoing cables. There is also less likelihood of exceeding an economical size for compound-filled busbars and incoming circuit-breakers.

For motor circuits, however, neither 6 600 nor 11 000 volts is an economical voltage, except for very large powers (as in mine hoists, etc.). On the other hand, motors with stator windings insulated for 3 300 volts are becoming more common for sizes over 100 h.p. There is little difference in cost between a 900-amp. 400-volt oil switch and a 300-amp. 3 300-volt oil switch (the frame size is often the same). The former will handle 600 kVA whereas the latter will handle 1 700 kVA. Moreover, when the oil switch is used as a stator circuit-breaker, the switching currents (for the same size of motor) are much reduced when the stator is wound for 3 300 volts instead of 400 volts. Thus a 500-h.p. motor would have a full-load current of about 100 amps. on 3 300 volts, but of about 650 amps. on 400 volts. Frequent switching at 650 amps. 400 volts will cause considerably more wear on the contacts of a 900-amp. 400-volt oil switch than switching at 100 amps. 3 300 volts, on the same size of breaker with contacts and insulation for 300 amps. 3 300 volts.

A 200-h.p. 3 300-volt motor can be designed with a standstill current of 100 amps. and can be switched direct on to the line repeatedly by a 300-amp. 3 300-volt oil switch with only the slightest marking of the oil-switch contacts. Experience shows, however, that the switching of 200-h.p. 400-volt motors by hand-operated oil switches can involve problems either in maintenance or in design which would not be present at the higher voltage.

The largest size of 400-volt oil switch which is an economical standard is of about 1 500 amps. capacity. Larger oil switches are occasionally supplied, but the demand is small and the cost of special manufacture heavy. The problems involved in carrying full load continuously on breakers of 1 500 amps. to 4 000 amps. are serious. Thus 1 500 amps. at 400 volts may be taken as an economical limit, and this corresponds to about 1 000 kVA. For a layout of motors which is likely (with eventual extensions) to total 1 000 h.p., the use of 3 300 volts for at least the main drives will probably be an economical proposition. It is, of course, very difficult to generalize and each case should be considered on its merits, but experience does show that the retention of 400 volts for distribution has in large installations presented problems, in carrying capacity, cabling, and rupturing capacity, which would not have arisen if the growth of the installation could have been anticipated and a nucleus of 3 300-volt distribution arranged at an early stage.

It would not always serve the same purpose to carry the 6 600-volt or 11 000-volt distribution farther into the layout (i.e. to break up the 400-volt network into smaller sections each fed by a 6 600- or 11 000-volt transformer substation). A decision depends chiefly on the size of the largest motors in the system.

To illustrate this in a borderline case where the largest motors are of about 150 h.p., consider a boiler-house layout involving motors of the following sizes: Induced-draught fan motors, about 150 h.p.; forced-draught fan motors, about 75 h.p.; secondary-air fan motors, about 25 h.p.; stoker motors, about 5 h.p.; etc. There are three chief ways in which the distribution layout could be arranged:—

(i) A 6 600/400-volt transformer could be mounted in the basement under each boiler, all the auxiliary motors

being fed from the 400-volt secondary of the transformer [see Fig. 4(*a*)]. Each boiler is then regarded as a unit, dependent on its own transformer, and a shutdown on a transformer involves only one boiler. The possible fault current on any l.t. circuit is limited to that which can be given by the reactance of a single transformer. No very heavy l.t. conductors or switches are involved, and the main supply cables are of an economical h.t. size.

use of remote-operated h.t. oil circuit-breakers can be made by the use of 3 300-volt contactors, as shown in Fig. 5.

CONTACTORS

The increasing use of contactors in motor circuits* is due to the increasing demand for remote operation and for frequent opening and closing of the motor circuit. With a.c. squirrel-cage motors in particular, the circuit

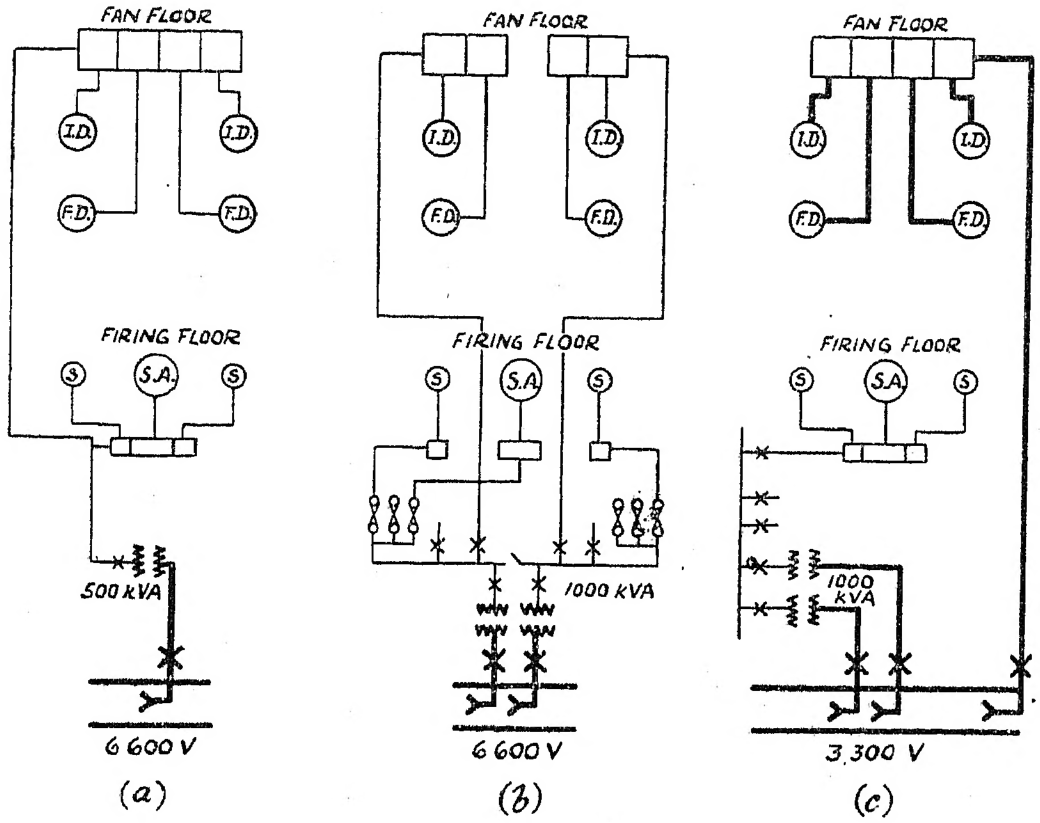

Fig. 4

(*a*) Layout of motors fed from 6 600/400-volt transformer.
(*b*) Layout of motors fed from 400-volt switchboard.
(*c*) Layout with large motors operating on 3 300 volts and smaller motors on 400 volts.

(ii) A group of boilers may be fed from a house-service switchboard supplied by duplicate 6 600/400-volt transformers [see Fig. 4(*b*)]. The busbars and incoming cables are of heavier section in this alternative than in the first, and the rupturing capacity on the l.t. side must be higher, but there is some compensation in the duplication of supply, which can be traced out in detail by reference to Fig. 4(*b*).

(iii) A distribution network operating at 3 300 volts can be provided for the induced-draught and forced-draught fan motors, and another distribution network at 400 volts for the smaller motors [see Fig. 4(*c*)]. The 3 300-volt stator switches for the 3 300-volt motors should be grouped together, with busbars, provided that the number so grouped does not involve a rupturing capacity exceeding the economical limit (on 3 300 volts) of 100 000 or 150 000 kVA. It is obviously uneconomical to provide a 3 300-volt oil switch at a distributing point and another 3 300-volt oil switch in the same circuit as a stator circuit breaker, unless there are special difficulties in arranging otherwise.

It is often necessary to operate the 3 300-volt stator switch remotely (as, for instance, in the case of an induced-draught fan motor on the fan floor, operated from push-buttons on a boiler instrument panel on the firing floor). A more economical arrangement than the

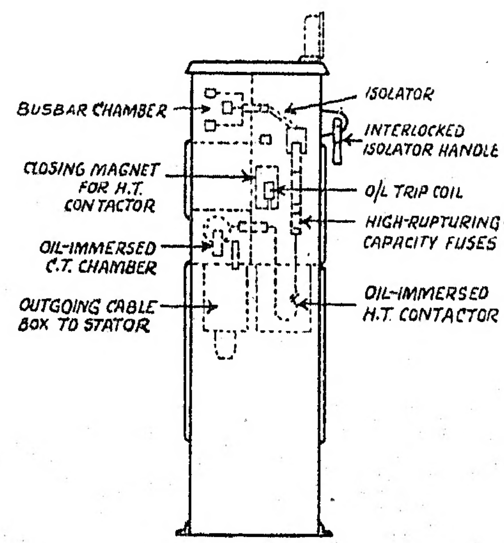

Fig. 5.—3 300-volt contactor panel with current-transformer-operated overload trips, high-rupturing-capacity fuses, and interlocked isolating switch.

has to be opened or closed under peak currents, and the demand for increasingly severe duties and for economy in contactor design and maintenance has brought the subject of contactor design into more prominence of recent years.†

* See Reference (2).

† *Ibid.*, (3).

While contactor starters have formed the subject of a separate British Standard Specification since 1923 (B.S.S. No. 155—1923, now incorporated in the general specification, B.S.S. No. 587—1935) there has been no separate British Standard Specification for contactors until the present year [CE(EL)366, in preparation]. In the preparation of this specification it was decided to ask the Electrical Research Association to investigate certain general problems in contactor design, such as contact wear and rupturing capacity,* and these investigations are now in progress.†

Different standards must be set for a.c. and d.c. contactors, the use of a.c. squirrel-cage motors usually involving higher peak switching currents. It is therefore useful at this point to illustrate a marked difference between the opening of an a.c. circuit and the opening of a d.c. circuit.

Short-break Switches

This fundamental difference is clearly shown by the introduction of the short-break switch for a.c. circuits only. With a length of break of only 0·01 in., currents of 100 amps. 230 volts can be broken easily on an

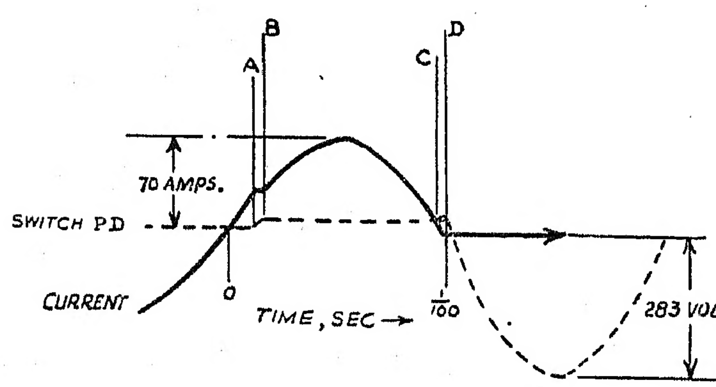

Fig. 6.—Short-break switch breaking 50-amp. 200-volt 50-cycle supply.

alternating-current supply, whereas the same switch would fail to break a fraction of an ampere on the same voltage on a direct-current supply. The principle of the action of the short-break switch is to separate the contacts by such a small gap that the arc energy in the gap is extremely small. As the current dies down to zero in its normal cycle, the production of arc energy is so low that the mass of the contacts can absorb the heat of this arc energy as it is produced. The arc is extinguished not by lengthening its path but by rapid cooling of the source of the arc. In the final diminution of the current to zero, the arc can hardly be maintained across even the gap of 0·01 in. by the voltage available across the contacts; and at the moment when the current passes through zero the arc disappears (see Fig. 6), and both the contact surfaces and the path of the arc are so cool that the recovery voltage cannot re-establish the arc, and the circuit remains open. The effect of power factor on the action of this type of switch would deserve further study, as also would the welding action that may take place on closing the switch with high peak currents, but in relation to contactors of normal design the principle of this switch illustrates a distinction between the design of a.c. and d.c. contactors that may be given still more weight in further research.

* See Reference (2). † *Ibid.*, (3).

Magnetic Blow-outs

The interruption of a d.c. circuit by a contactor requires the use of a magnetic blow-out if a long flaring arc is to be avoided. A d.c. contactor with magnetic blow-out which would interrupt 100 amps. easily has been known to fail to break a ½-amp. inductive load, the magnetic blow-out having no effect at this low current. On an a.c. circuit, however, contactors can be made to break currents up to 2 000 amps. or more without the use of blow-outs, and on small currents the arc is usually negligible. A striking illustration is the breaking of a 100-amp. 400-volt circuit (with resistance load) on two similar contactors, one fitted with a blow-out and one without. Without a blow-out, the arc is hardly visible. With a blow-out, the arc shows a substantial flash.

Operating Experience

At low power factors, the arcing on an a.c. contactor is more serious than at unity power factor. The point in the current wave at which the arc commences affects the arc that may be struck, and under the same circuit conditions the arcs in successive tests may vary very considerably. There are so many factors involved in breaking an a.c. circuit that it is difficult to compare the results of tests made under different circuit conditions. The following summary, however, deals with the operation of contactors, not from a theoretical standpoint, but from experience of various forms of contactors when operating under conditions of severity that result in breakdown. It should be added that in commercial practice the occurrence of these failures is very infrequent.

(i) Arcing to case.

This type of fault is most likely to occur on d.c. enclosed contactors used on 500-volt systems with one pole earthed, so that the potential from one pole to earth is double that of the more usual circuits with mid-wire earthed.

Flashovers to case on a.c. contactors are infrequent, but are more likely to occur (*a*) in designs that have been cramped, particularly in " built in " designs where space is at a premium; (*b*) on peak currents at low power factors; (*c*) at high altitudes, or where there is dust in suspension inside the contactor case; (*d*) after repeated operations in quick succession, so that the case becomes filled with ionized gas; (*e*) on supplies obtained through a frequency-changer giving high frequency exceeding 100 cycles per sec.

The remedies for this type of fault are obvious.

(ii) Arcing between phases.

On heavy loads at low power factor the arc may be produced at a rate higher than that at which the ionized gas can escape from the arc shields, and the arc may spill over from phase to phase. If the arc is boxed-in above the contacts, the pressure produced in the box may drive hot gas out from the bottom of the box and produce a short-circuit between the live poles of the open contactor. If the arc passes out through narrow slits its exit at the top will be cooled and there is little danger of

an arc striking across from phase to phase unless the exit of the gases at the top is so restricted that they are forced out also at the bottom, again with the likelihood of short-circuit between phases. With sufficient shielding between phases and ample room for the hot gases to rise from the contacts, there is little likelihood of flashover between phases.

(iii) Welding in making circuit.

This may be due to a number of causes, as follows: (*a*) Chattering may occur owing to the contactor coil circuit being closed indecisively. This again may be due to hesitant pressure on a start push-button, or to weak or dirty auxiliary contacts, aided by vibration or even by the impact of the contactor closing. (*b*) Contact may be made on a point or bead left by previous arcing, welding being more likely to occur if the contact pressure is insufficient. (*c*) The impact of the moving contact on the fixed contact may result in contact bounce. This can be most clearly demonstrated on a condenser load (see Fig. 7). (*d*) Very frequent operation at peak currents and low power factors can heat up the contacts faster than the heat can be conducted away from the arc craters.

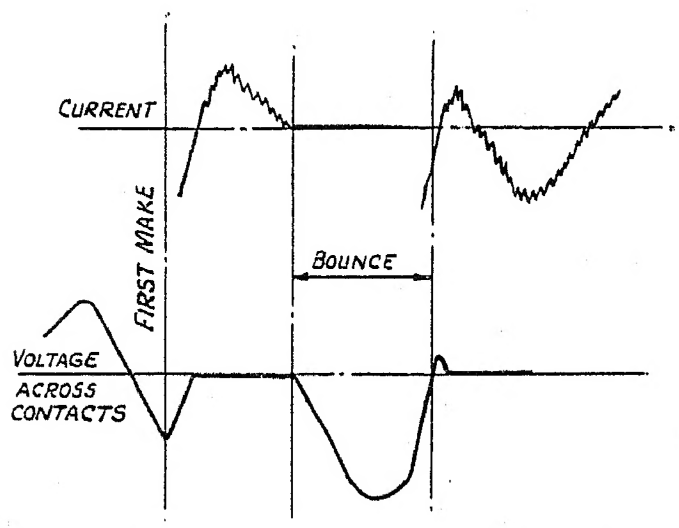

Fig. 7.—Oscillogram of contactor chattering badly when closing—shown on capacitance load.

(*e*) When closing on extremely heavy short-circuits, the moving contacts may be blown off as soon as they touch by electromagnetic forces, which on a.c. circuits will be of a pulsating character (see Fig. 8 on Plate 2).

The making and breaking of circuits by contactors arranged to exhibit some of the faults mentioned above can be demonstrated by means of slow-motion films.

In spite of the possible faults described above, automatic control gear involving the use of contactors instead of hand-operated switches is being increasingly used. For frequent operation on peak currents, contactors are consistently satisfactory when properly designed and mounted and conservatively rated.

It is interesting to note that motor control gear for frequent operation has developed on the general basis of air-break contactors, while distribution circuit-breakers and hand-operated motor control gear are mainly of oil-immersed types. Research work in several countries has confirmed this practice, since endurance tests have shown more contact wear on oil-immersed switches than on air-break switches of equivalent design. A distribution oil-switch is designed primarily for rupturing capacity and is not frequently opened or closed. Hand-operated starters are more frequently operated than distribution circuit-breakers, but are not rated for the frequent service which may be required of contactor gear. Oil-immersed starters, switching peak currents which are well above their continuous rating, at frequent intervals, may need renewal of contacts after a number of operations which would not cause any undue wear on the contacts of equivalent air-break contactors.

Contactors may, of course, be oil-immersed for various reasons, such as for use in acid-laden atmospheres or in order to use the insulating properties of oil to reduce clearances between phases, as in small 400-volt designs or for high-tension work.

OVERLOAD TRIPS

The origin of severe overloads and short-circuits in motor circuits is likely to be on the motor side of the starter or in the starter itself, and the overload protection afforded by the starter is therefore of importance. Thermal trips may be more readily damaged by short-circuit than magnetic trips unless the duration times of short-circuits are taken into consideration. A directly heated thermal trip for a small current rating may easily fuse before the circuit can be cleared by a back-up circuit breaker or even by a sub-circuit fuse. It must be remembered that the thermal trip has not only to open its trip circuit but to carry the main current until the contactor itself clears the circuit. In a test to show this point, a 5-amp. thermal trip, which would clear 200 amps. when opening the circuit mechanically, was found to fuse before the circuit was cleared, when the thermal trip was arranged to open a contactor-coil circuit, because of the slight delay caused by the fact that two mechanical movements had to be made—first the movement of the thermal trip and then the movement of the contactor magnet.

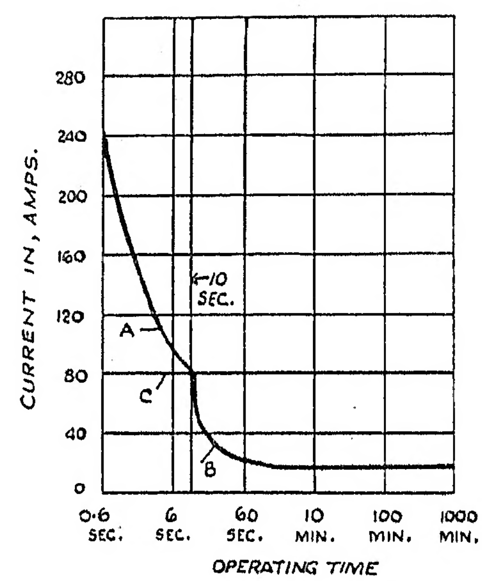

Fig. 9.—Operating times for thermal-trip and high-rupturing-capacity fuses on various overloads.

A. Time/current curve of a cartridge fuse.
B. Time/current curve of thermal over-current trip (25 per cent overload setting).
C. Maximum motor starting-current 80 amperes.

With an indirectly heated thermal trip it is easier to proportion the calibration curve of the thermal trip to the operating curve of back-up fuses so that, on overloads

up to the stalling current of the motor, the thermal trip operates before the fuse, and on any short-circuit above stalling current the fuse operates in time to prevent any damage to the heating element of the indirectly heated thermal trip. The use of different sizes of fuses for back-up protection does not (within reason) make this system of protection unsound, although a fuse rated to carry 3 to $3\frac{1}{2}$ times the normal current of the circuit is found to give the best results in the usual application (protection of induction-motor circuits).* This point is illustrated in Fig. 9.

RUPTURING CAPACITY OF STARTERS

The matter of rupturing capacity in motor circuits is referred to in the British Standard Specification for motor starters,† where it is specified that the starter shall be capable of breaking, on a.c. supplies, 6 times the motor full-load current (a footnote is added to the effect that a fuse or a circuit breaker should be fitted for dealing with short-circuits). The rupturing capacity of the starter itself does not, according to this rule, become even 1 000 kVA under motor sizes of about 150 h.p. It is

Table 1

LENGTH OF 400-VOLT 3-CORE CABLE REQUIRED TO REDUCE POSSIBLE SHORT-CIRCUIT (FROM UNLIMITED SUPPLY) TO BREAKING CAPACITIES SPECIFIED BELOW

Size of supply cable	Normal carrying capacity of cable (amps.)	Length of cable required to limit to:—		
		100 kVA	1 000 kVA	10 000 kVA
37/·093 (P.I.)	300	—	—	165 yds.
19/·083 (V.I.R.)	100	—	660 yds.	66 yds.
7/·036 (V.I.R.)	20	—	150 ft.	—
3/·029 (V.I.R.)	5	400 ft.	40 ft.	—

therefore important to consider what may happen to the starter on more severe short-circuits while the circuit is being cleared by the fuses or circuit breaker used for back-up protection. A small starter or fuse-box may be in a position where the possible short-circuit value is 25 000 kVA, or it may be fed by a sufficient length of small cable to reduce the possible short-circuit value to a very low figure. Table 1 shows how the possible short-circuit kVA may be reduced by the impedance of supply cables, whatever power is available at the supply end of the cable.

In contrast to the scale on which the rupturing capacity of transmission switchgear is being investigated, the attention paid to short-circuit protection on motor and other industrial circuits is often too cursory. The results of e.h.t. research have not been fully related to the problems of rupturing capacity in l.t. circuits by the large number of engineers concerned in l.t. distribution.

The number of engineers who must concern themselves with the problems of rupturing capacity in e.h.t. switchgear is small compared with the number of engineers who are concerned with l.t. switchgear, i.e. with the application of electrical power in motor circuits. The industrial users of electricity, the consumers' engineers of supply authorities, and the manufacturers of industrial switchgear and motor control gear, are all concerned with protection against short-circuits.

Failure to clear a short-circuit on a works sub-circuit does not generally have the disastrous results which may arise from failures in e.h.t. switches, but there may be danger of personal injury and considerable expense in stoppage of plant and renewal of equipment. The problems of rupturing capacity in l.t. circuits are becoming more pressing, for several reasons:—

(i) Owing to the large scale on which most industries are using electrical power, the power available in the main distribution circuits is increasing, not only in total but also in concentration. In many such cases there has been a reluctance to use 3 300 volts or 6 600 volts within the works distribution system, and the main distribution has been carried out from a 400-volt switchboard which is capable of supplying a very heavy short-circuit power—heavy, that is, in relation to the knowledge available in the industry. Far more, for instance, is known of the behaviour of 6 600-volt oil switches on short-circuits of 100 000 kVA than of the behaviour of 400-volt switches on short-circuits over 25 000 kVA.

(ii) As private generators have been superseded by public supply transformers, the short-circuit power available has increased considerably. A 1 000-kVA generator will give a short-circuit of the order of 6 000 kVA, but a 1 000-kVA transformer fed by a normal e.h.t. network will give a short-circuit of the order of 20 000 kVA.* The transformer reactance is usually the chief impedance of practical importance on the low-tension side of transformers fed from h.t. networks (e.g. on the high-tension side of a 1 000-kVA 6 600/400-volt transformer, short-circuits of 150 000 kVA or 250 000 kVA may be possible; but on the low-tension side the maximum possible may be only 20 000 kVA).

(iii) Because of wider knowledge and because of the interest that has been aroused in the industry in general in the subject of rupturing capacity, occasional failures of protective switchgear to clear "dead short-circuits" are regarded less tolerantly. There are unusual circumstances in every failure of this kind, but the protective switchgear is bought as an insurance against them.

High short-circuit values can be almost always avoided on l.t. networks if there is a will to do so, and if the basic idea of the layout includes this intention.

TRANSFORMER SIZES

Insufficient use is often made in large installations of the choke effect of transformers on low-tension short-circuit values. Installations grow up on low voltage, and the industrial engineer has need to borrow some of the point of view of the supply engineer who thinks in terms of high-voltage distribution with a number of l.t. transformers each placed as close as possible to its section of the load and not usually larger than 500 kVA. Larger transformers involve heavier short-circuit values, and over 25 000 kVA very little generally is known of the performance of l.t. switchgear or fuses. Larger sizes of

* See Reference (4). † *Ibid.*, (5).

* See Reference (6).

transformers with 400-volt secondaries also involve the use of heavier currents than are convenient.

The principles used in electric resistance welders show how easy it is to heat a junction with a low-tension heavy-current supply. Heating troubles on switches closed for long periods are more likely on currents over 600 amps. Cables are expensive and difficult to handle. Busbars joining a bank of two or three transformer switches above this size become heavy and, if ironclad and unventilated, the rating in amps. per sq. in. must be considerably reduced. Eddy currents become noticeable over 300 amps. and become a more serious factor in design above 600 amps. Even the operation of switches becomes burdensome, and contacts are burnt by operators not having the weight or knack to close heavy-current hand-operated 3-phase oil switches without drawing back after the first touching of the contacts.

FUSE PROTECTION

Semi-enclosed (non-cartridge) Fuses

With regard to fuses, the present British Standard Specifications* give short-circuit ratings for ordinary fuses as shown in Table 2.

Table 2

Normal carrying capacity	Short-circuit rating at 230 volts		
amps.	amps.	kVA	kVA × 3
15	1 500	230	690
30	2 000	460	1 380
60	4 000	920	2 760
100	6 500	1 495	4 485

For three fuses in a 400-volt 3-phase circuit, it might be considered that the 3-phase short-circuit rating of the three fuses (corresponding with the short-circuit rating of a 3-phase circuit breaker) would be 3 times the figures of kVA for one fuse on 230 volts, or $\sqrt{3}$ times the kVA rating of one fuse on 400 volts. There is, however, no guarantee that a fault current will divide equally between the three phases, and one fuse may be called upon to break a higher short-circuit than that corresponding to the 3-phase short-circuit value of the circuit divided by $\sqrt{3}$.

Referring to Table 1, in the light of the figures given in Table 2, it will be seen that a 60-ft. length of 3/·029-in. cable is required to reduce the possible short-circuit value to within the British Standard limits of rupturing capacity of three 15-amp. rewireable fuses, and that a 20-amp. cable (or, say, 7/·036 in.) feeding a fusebox would have to be 150 ft. long to limit the short-circuit to 1 000 kVA. The larger cables will pass short-circuits so much in excess of the ratings of any of the fuses tabulated in Table 2 that if the supply is available, the small fuses in the circuits can only be saved from destruction by (1) actual rupturing capacities higher than those laid down by B.S.S. No. 88—1931, or (2) the rapid clearing of the circuit by some back-up protection, or (3) by some feature of the actual short-circuit in its service form which delays its full severity. The degree of immunity from serious trouble with short-circuits enjoyed even by users who have large short-circuit values available in their sub-circuits is partly due to the rarity with which short-circuits occur and partly to the causes mentioned above. With increasing use of large transformer capacities, however, more attention is being and should be given to this matter.

* See Reference (7).

Testing Facilities

It is not necessary to install a large testing plant to obtain short-circuit values of the order of 5 000 kVA, and yet the available data on the performance of wired fuses on a.c. short-circuit values of 2 000 kVA to 5 000 kVA are extremely scanty. If the possible short-circuit values in ordinary industrial sub-circuits were calculated, it would be found that this range of values must be extremely common. Further, a short-circuit test on a d.c. battery supply may provide more consistent short-circuit conditions than those obtained on an a.c. supply (where the moment of the commencement of short-circuit may vary in relation to the phase cycle), but the latter is now the usual supply in practice and a d.c. test may not be a correct guide to the performance of a fuse on alternating current. A 3-phase test (repeated a number of times) close to the terminals of a transformer capable of giving the value of short-circuit required for the tests proposed more nearly corresponds to practical conditions than a d.c. battery test.

High-Rupturing-Capacity Fuses

The time of operation of high-rupturing-capacity fuses on severe short-circuits is very rapid (see Fig. 10). A 30-amp. cartridge fuse on a 380-volt circuit capable of giving 40 000 r.m.s. amps. (maximum asymmetrical peak current available, 100 000 amps.) has been shown to blow in 0·001 sec. before the current rose above 2 500 amps. Although the conditions of this test are equivalent to over 40 000 kVA at 660 volts, 3-phase, the time of operation of the fuse is so short that the risk of damage to the circuit protected must be extremely slight; and in fact small starters of the simplest type have been found to be in good working order after severe short-circuits when

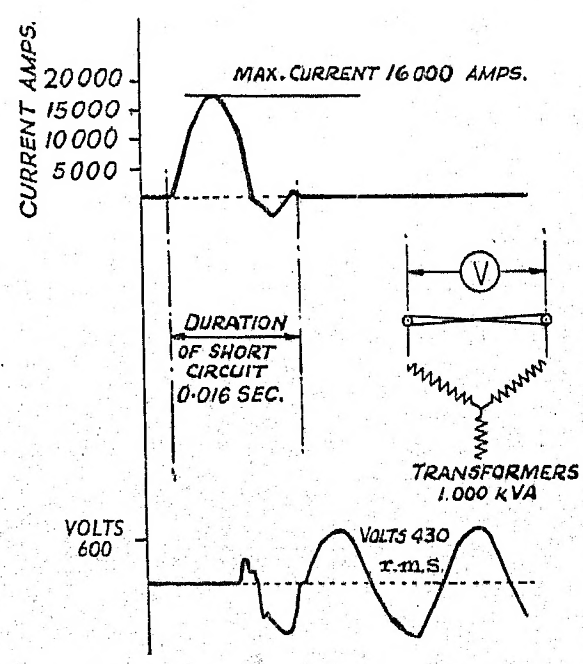

Fig. 10.—Oscillograms for 500-amp. fuse on 1 000-kVA transformer short-circuited as shown.

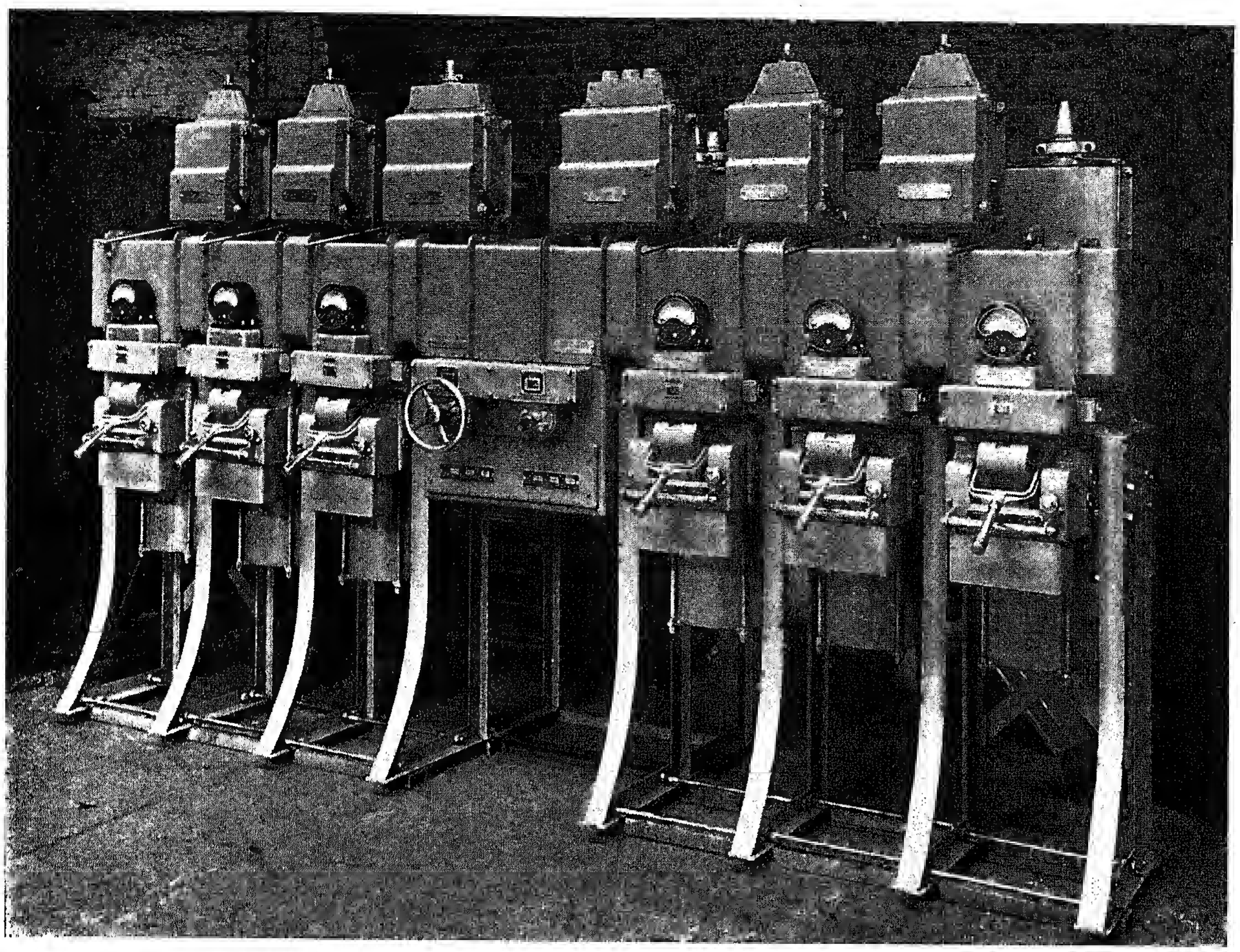

Fig. 2.—Motor-control switchboard including switch-fuses for feeding separate starters.

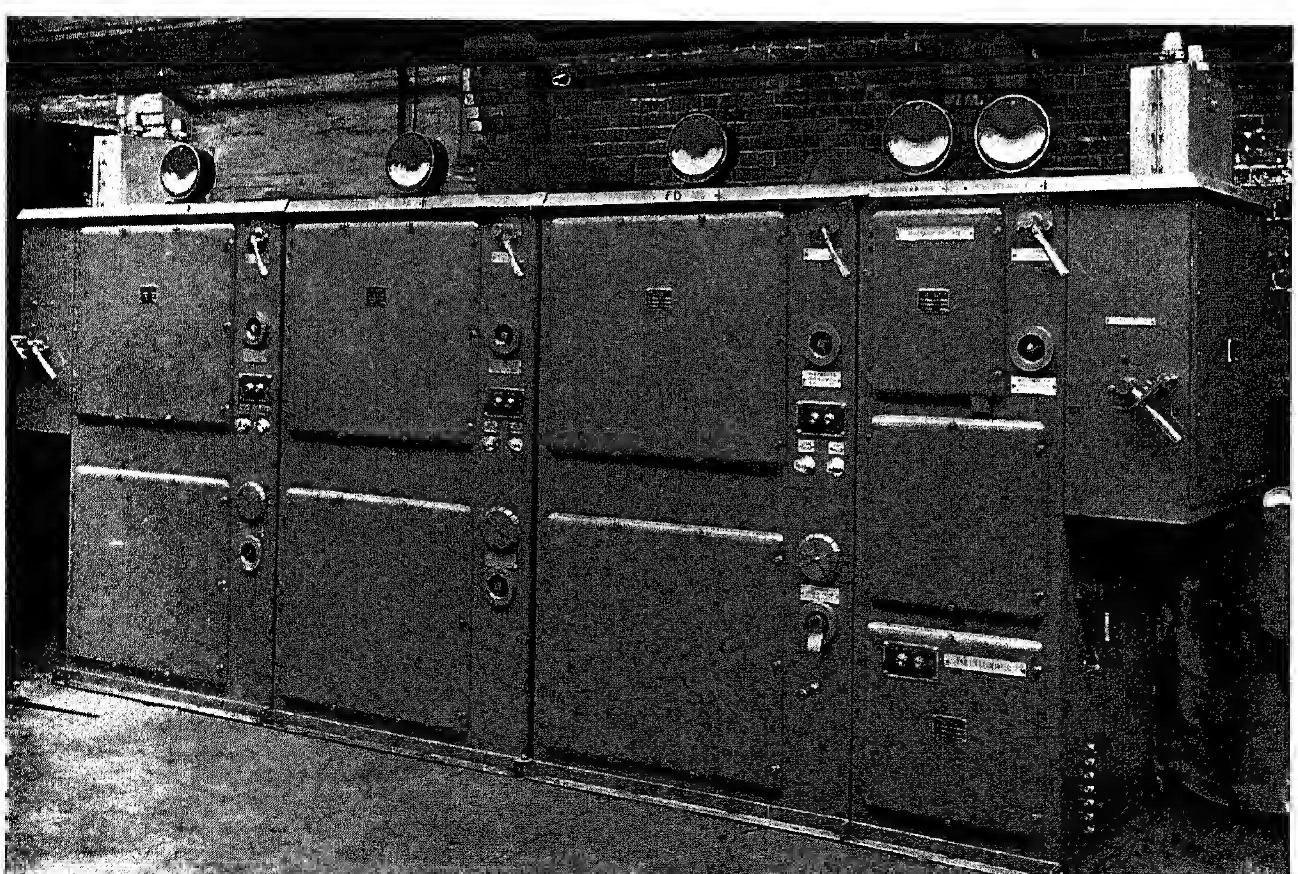

Fig. 3.—Starter switchboard with busbars and ring-main isolators.

Plate 2

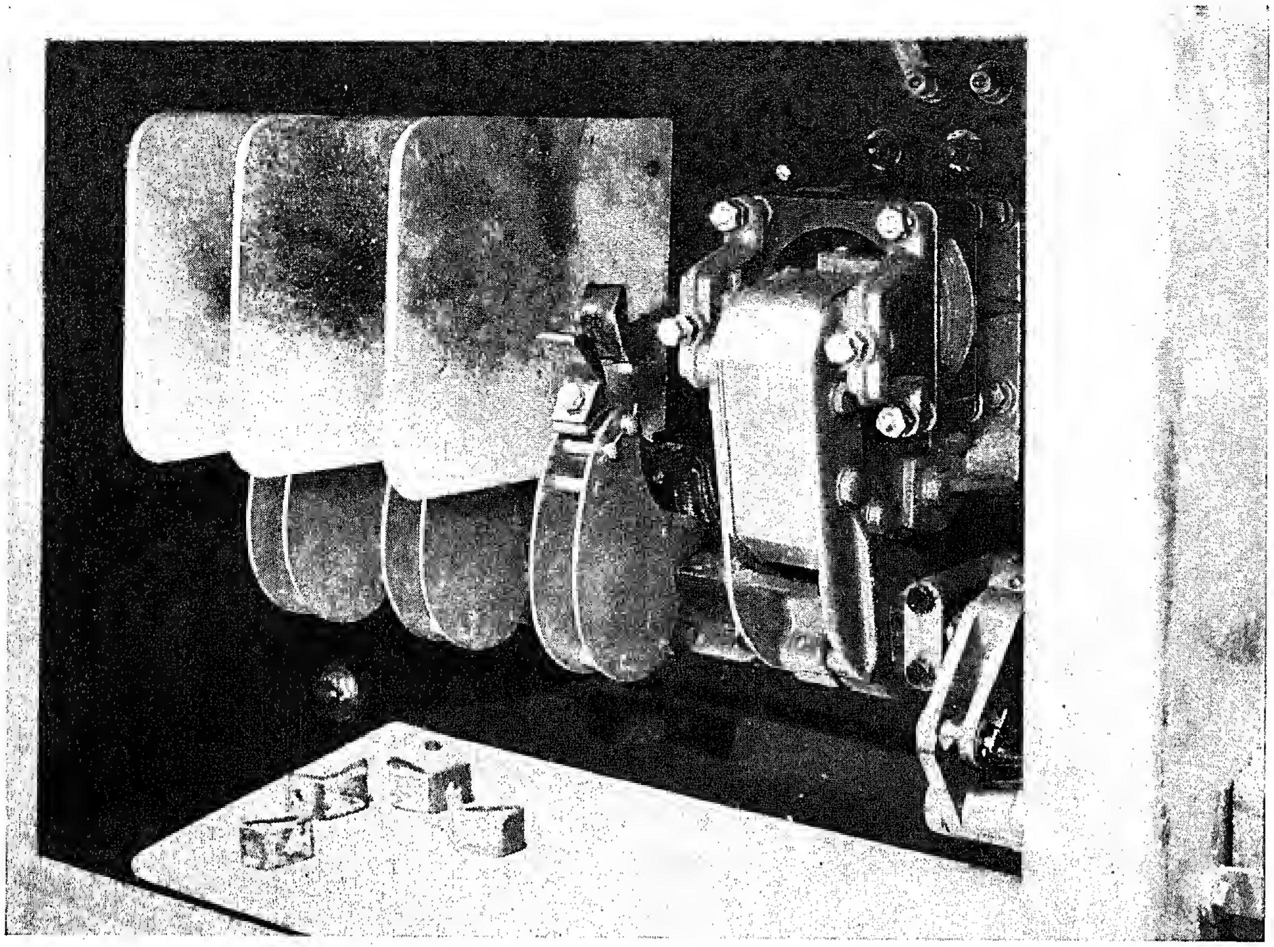

Fig. 8.—Latched-in contactor after test at 15 000 kVA (400-volt supply) maintained for 1 sec. (butts removed for examination).

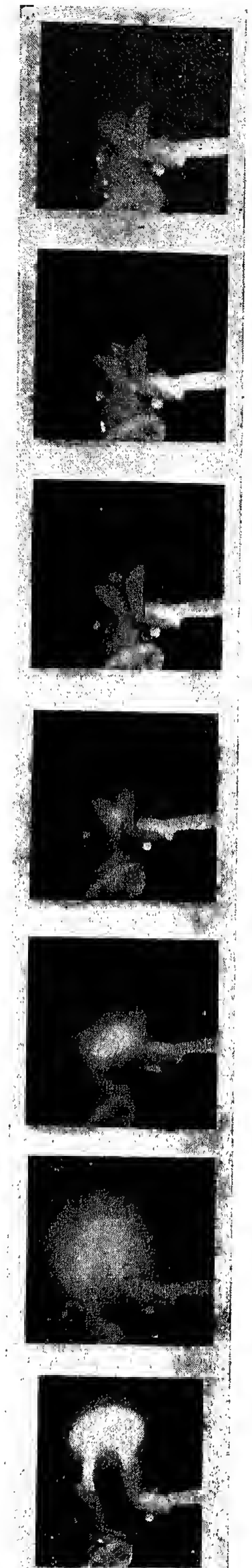

Fig. 12.—Pictures from film showing contactor making and breaking 6 amps. (inductive) direct current.

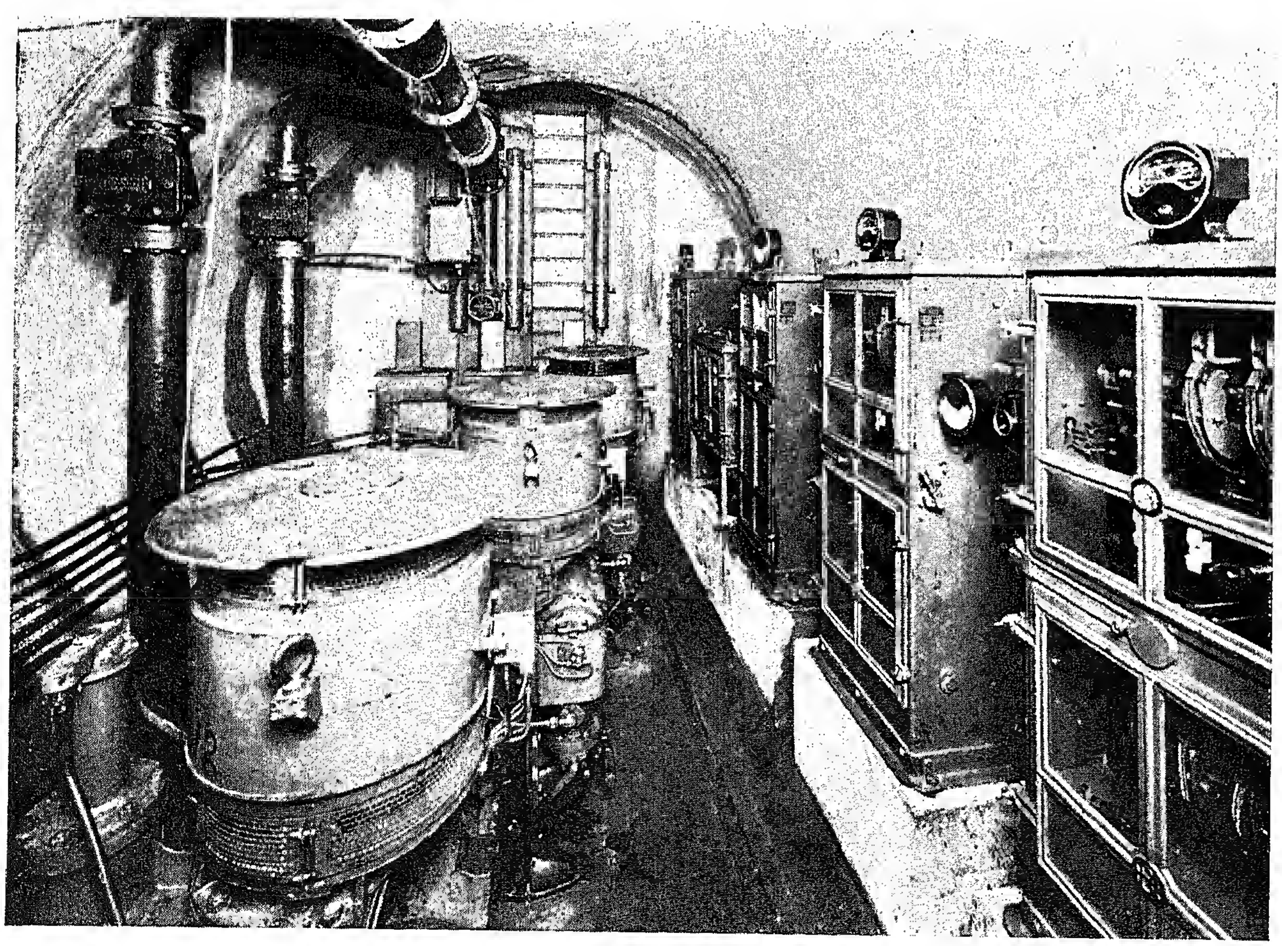

Fig. 15.—Insulation indicators fitted to starters in underground pump room.

protected by such fuses, even though without such protection they would have been destroyed by the short-circuit power available.

As the size of fuse increases, the operating time increases (see Fig. 11) for the same value of r.m.s. short-circuit current. On a value of 10 000 r.m.s. amps., the operating times (including arcing time) of one make of cartridge fuse increase from 0·001 sec. for a 30-amp. fuse to 0·01 sec. for a 300-amp. fuse and to 0·05 sec. for a 700-amp. fuse. A circuit breaker fitted with magnetic overload trips has, on the other hand, a more definite minimum time of operation because there are two mechanical movements which must take place—first the movement of the armature of the overload trip and then

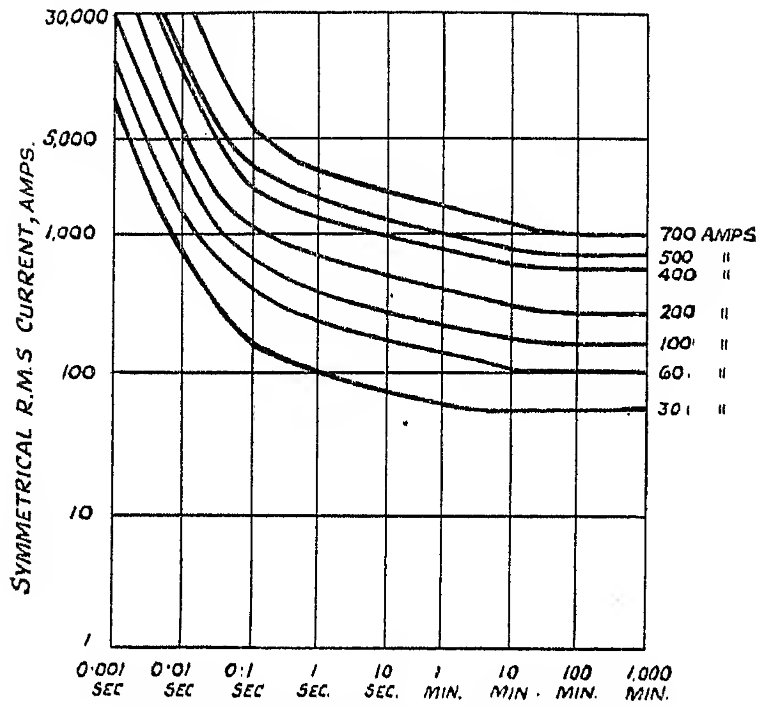

Fig. 11.—Operating times of high-rupturing-capacity fuses at various currents.

the movement of the switch contacts. These movements may take from 0·01 to 0·1 sec., according to the size of the circuit breaker.

Thus in a circuit including both sub-circuit cartridge fuses of, say, 100 amps. and a main circuit-breaker of, say, 500 amps., the latter having an operating time of 0·04 sec. (pre-arcing time 0·03 sec. and arcing time 0·01 sec.), the fuse would blow before the circuit breaker began to arc on short-circuits exceeding 1 000 amps. or twice the current rating of the circuit breaker. On small overloads the circuit breaker, if delayed by time-lags, would also be slower than the fuse (which would operate in 0·1 sec. on 500 amps.), and therefore in every overload or short-circuit condition the sub-circuit fuse would operate before the circuit breaker. With other sizes of fuses and circuit breakers it will be seen that it is quite possible for the main breaker to come out first on lesser short-circuits and for the sub-circuit fuses to clear first on severe short-circuits.*

SHORT-CIRCUIT RATINGS OF CIRCUIT BREAKERS

The particular feature of low-tension rupturing capacity in contrast to the usual problems of rupturing capacity on high-tension circuits is the high value of the short-circuit currents in l.t. circuits. This will be seen from Table 3, the middle columns of which show the rupturing capacities most frequently specified for circuit breakers on various voltages.

A short-circuit current of 15 000 amps. corresponds to over 150 000 kVA on 6 600 volts, but only to a little over 10 000 kVA on 400 volts.*

Remembering that electromagnetic forces increase as the square of the current, and even allowing for the smaller clearances of the low-tension breaker, it will be recognized that for short-circuit values over 25 000 kVA (36 000 amps.) the electromagnetic forces on the cross-arm and mechanism must be seriously reckoned with.

The electromagnetic forces tending to force the contacts apart or to press them together (according to the design) are also specially important in dealing with l.t. designs for high rupturing capacity. If sparking fingers are used care must be taken that these are not blown off before the main contacts have parted, and that chattering, hesitant opening, or welding, do not occur. When closing on short-circuit also, trouble may be experienced similar to that which is already known to be a serious factor in

Table 3

Rupturing Capacity of Distribution Circuit-Breakers†

Supply	Low	Medium		High
volts	kVA	kVA	amps.	kVA
400	5 000/10 000	25 000	36 000	50 000
3 300	33 000	100 000	17 600	250 000
6 600	75 000	150 000	13 000	500 000
11 000	100 000	250 000	13 000	750 000
33 000	250 000	500 000	8 800	1 000 000

the design of high-rupturing-capacity circuit breakers for higher voltages.

It is also characteristic of l.t. circuit breakers that the proportion of the energy liberated when an arc is struck, which is dissipated at the contacts, is higher than for higher voltages. The contact drop of potential is approximately 30 volts (double break) whether an arc is struck at 400 volts or at 6 600 volts.‡ [On this basis the "contact" energy involved in breaking 25 000 kVA (36 000 amps.) in 0·01 sec. (one half-cycle) would be 36 000 × 30 × 0·01 watt-sec. per phase, or 10·8 kW-sec.]. The proportion of the total energy released in the circuit breaker which is absorbed in contact energy (heating, melting, and vaporizing the contact tips) may be one-third of the total energy in an l.t. oil switch§ but only one-tenth or one-twentieth of the total energy in a 6 600-volt switch. In a particular instance, a short-circuit of 150 000 kVA at 0·1 power factor broken in 0·04 sec. with a low tank pressure gave an arc energy of 400 kW-sec., or at the rate of 10 000 kW (*cf.* 150 000 kVA at 0·1 p.f. = 15 000 kW).

In an l.t. circuit breaker, the values of kVA and arc energy in practical examples would be much lower (e.g. 15 000 kVA at 0·1 p.f. equals 1 500 kW, or 15 kW-sec. per half-cycle); also the impedance of even short supply

* See Reference (8).

* See Reference (10). † *Ibid.*, (9). ‡ *Ibid.*, (11). § *Ibid.*, (11).

connections would be of more practical importance. Thus a calculated short-circuit value of 15 000 kVA at the terminals of a transformer was lowered to 10 000 kVA by the reactance of the short leads to the l.t. breaker and the reactance of the breaker itself. A 400-amp. 400-volt breaker of 0·0015 ohm internal impedance per phase will give a drop of nearly 40 volts across the *closed* switch when passing a current corresponding to a short-circuit of 15 000 kVA (22 000 amps.).

In an h.t. switch the greater proportion of the arc energy is absorbed in breaking up the oil and in heating the gases formed.* At each break a gas bubble may be formed which grows so rapidly that adjacent bubbles would meet but for the interposition of phase barriers, and in the same way the gas bubble might reach the tank side but for the interposition of insulating tank liners. Further, the gas produced has a high acetylene content and there is a risk of a secondary explosion when the hot gases meet the air above the oil (under pressure), especially if the head of oil above the contacts is small.

It is therefore desirable to shorten the time for which the arc persists, "pressure" on the arc bubble and "cooling" of the arc path being the chief principles used. To use a simple illustration, it is more difficult to make a sparking-plug spark "under compression" than at atmospheric pressure, and (to speak in simple inexact words) a "cool arc" is a contradiction in terms.

In dealing with high voltages, high pressures are required to ensure that the arc will be suppressed at an early current zero, pressures of the order of 1 000 lb. per sq. in. being employed in boxed contacts to secure arc suppression at the first current-zero. With contacts moving at an average speed of 8 ft. per sec. and a frequency of 50 cycles per sec., a travel of 4 in. would occupy about four half-cycles. With the smaller switches generally used for low-voltage work (in which also the contacts travel a shorter distance before parting), the average speed of travel may be as low as 2 ft. per sec., so that a break of 1 in. would occupy four half-cycles and three current-zeros would occur in this travel. Mr. Anderson† has shown that a current of 4 000 amps. at 380 volts (non-inductive) can be interrupted in 1 in. with a speed of travel of approximately 6–12 ft. per sec. or, alternatively, in 0·5 in. with a speed of travel of approximately 2–4 ft. per sec., the arc duration being about one half-cycle in the first alternative and three half-cycles in the second. The best speed of travel for low-voltage circuit breakers of various sizes deserves further study. It should also be noted that although the movement of the moving cross-bar can be easily recorded and the variation from constant velocity allowed for in calculation, the arc path may not be straight.‡ In fact, the form of the arc path may vary within each half-cycle.

The influence of pressure on arc duration could also be further studied at low voltages, since on high rupturing capacities (for the given voltage) the same problems occur as in h.t. circuit breakers.

ARC SUPPRESSION

Effect of Pressure

The pressure produced in a closed or nearly closed tank by the gasification of the oil is a vital factor in rupturing capacity. The pressure produced by the gas is for a given switch a function of the amount of gas produced, which is itself some function of the arc energy, which is again some function of the kVA broken and the duration of the arc.*

Since a switch must break any short-circuit up to its maximum rated kVA, a switch of high rupturing capacity based on pressure obtained from a strong tank and an air cushion must be designed for three sets of conditions: (1) On smaller short-circuits the length of break must be sufficient to cause the arc to be extinguished at the low pressures then available; (2) on medium short-circuits the pressure must be sufficient to prevent the arc bubbles growing too large; (3) on heavy short-circuits the pressure must not build up so rapidly that the tank bursts with the pressure impulse.

In both condition (2) and condition (3) a further complication is the risk of secondary explosions caused by the gases (with a high acetylene content) reaching the compressed air in the air cushion at a high temperature.

Cooling Effects

In addition to controlling the pressure so that the arc bubble is under pressure at current zeros, it is also desirable to cool the arc bubble and if possible the contact surfaces from which the arc is fed. This should be done without permitting the voltage across the arc to be high during the swing of the current through its peak value, as this will increase the arc energy. (The arc should ideally be short while the current is passing and lengthen as the current is dying to zero in its normal wave-form.) The gas bubble may be cooled by blowing it between cooling plates, or by turbulence, or by oil movement, or by any combination of these effects which can be applied in practical form. Apart from attacking the gas bubble itself, the arc may be attacked at its roots on the contacts themselves. It is easy to demonstrate this factor by breaking a small d.c. circuit in air. At the moment when the current is finally interrupted there lies between the contacts an ionized globe of hot gas which becomes dissociated from the contact surfaces (see Fig. 12 on Plate 2). Once this globe of highly conductive vapour is finally detached from the contacts, the current is interrupted. It is difficult to apply this principle in practical form to the interruption of high-power arcs because of the rapidity with which the contacts begin to burn and the difficulty of cooling an incandescent crater, but in the interruption of normal or overload currents it is comparatively simple to cool the contacts sufficiently to reduce the burning caused by frequent operation, and on short-circuit currents some mitigation of the arc energy can be effected by suitable applications of this principle.

Established Practice, and Progress

Since the E.R.A. summarized in 1921 and 1922 the information at that time published† on the phenomena of switching and arcing, a vast amount of research work has been undertaken on the problems of rupturing capacity. Most of this work has been undertaken on voltages of 6 600 volts and over, and on breakers designed for rupturing capacities from 150 000 kVA to

* See References (11) and (12). † *Ibid.*, (13). ‡ *Ibid.*, (14).

* See Reference (15). † *Ibid.*, (16).

1 500 000 kVA.* The data obtained from this research work are very complex and a great deal remains to be done, not only in pursuing these researches but also in collating the information already obtained.† It requires judgment as well as theoretical knowledge to apply the results of technical research on rupturing capacity because of the number of variants, whose interaction it is difficult to foresee under all conditions of service and under short-circuit conditions of different severity. The results of technical research must be given practical form, or progress will be blanketed by fear of change from established practice. The changes in design made, however, as a result of improved theoretical knowledge must be applied in practice with care and with special regard to those practical rules which are well grounded in experience, deviations being checked step by step by test and by practical application under service conditions.

Pre-arcing Period

There is a further consideration which is specially important in l.t. circuits protected by circuit breakers of adequate rupturing capacity, but comprising a network of small cables, motor windings, and motor starting and protective switchgear. The energy released into such a circuit by a serious fault may be very considerable before the breaker begins to arc, since the breaker may take 0·05 sec. to come into operation (i.e. from the energizing of the overload relay by the short-circuit to the parting of the contacts).

An energy of 5·6 kW-sec. will raise to melting point and melt 1 cm^3 of copper, but another 47 kW-sec. is required to turn the molten copper thus produced into vapour. Thus 1 000 kW of energy can change 1 cm^3 of copper into vapour in 0·05 sec.

The melting of a copper conductor may be serious enough in the stoppage of an important unit of plant, but the explosion of metal into vapour inside a terminal box or small switchbox during the pre-arcing period may be dangerous to personnel, even though the circuit breaker then clears the short-circuit in one half-cycle.

ANTICIPATION OF SHORT-CIRCUITS

Finally, because prevention is better than cure, it is worth while to consider how short-circuits occur on motor circuits in practice. For short-circuit tests it is usual to simulate a complete and instantaneous breakdown of insulation, and from the point of view of the competence of the circuit breaker or fuse to isolate a faulty section under any circumstances, the most serious condition that may occur in practice must be guarded against. There are, however, many breakdowns of insulation which are not sudden in their origin. Insulation may be affected gradually by excessive heat. Dampness can cause surface tracking or penetration of insulation which has become hygroscopic. There may be an accumulation of conductive dust, or dust which becomes conductive when damp. Insulation may become abraded by mechanical wear or by expansion and contraction under variations of temperature, or by repeated electromagnetic stress. Peak voltage surges arising from the secondary effects of lightning discharges or caused by excessive recovery voltages in the operation of fuses or circuit breakers may affect the insulation at weak points (see Fig. 13). If an incipient fault could be detected before a weak spot in the insulation broke down, it might be remedied without the dislocation caused by even a successful clearing of a

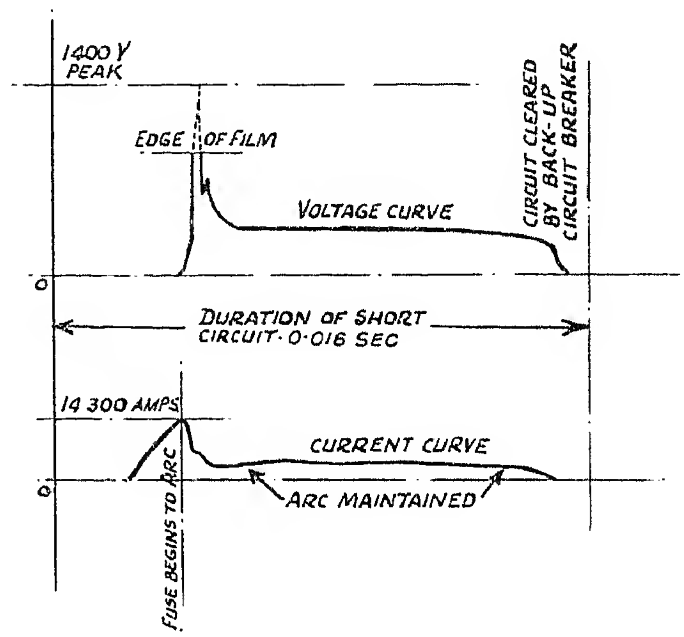

Fig. 13.—Oscillograms of 100-amp. rewireable fuse failing to clear short-circuit on 400-volt d.c. battery.

short-circuit. The leakage of current through insulation can be checked periodically by a megohm tester and in many installations a more frequent use of such an instrument would be an advantage, though the testing of insulation of even a simple factory network with any real thoroughness is not an easy matter. To test any sub-circuit between phases it is necessary to cut off the supply, to close each switch and starter in any circuits fed from this sub-circuit, and to disconnect one end of each shunt coil. (In important sub-circuits and especially in process work and other applications where an unexpected stoppage may involve heavy financial loss, provision may

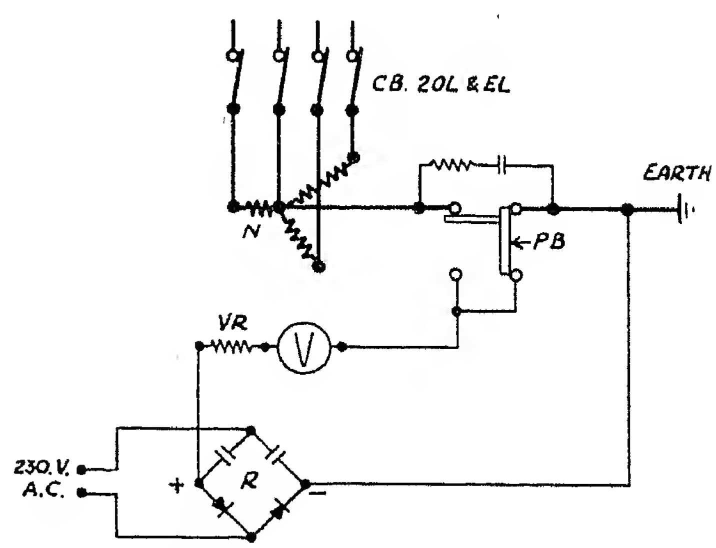

Fig. 14.—Insulation indicator for low-voltage 3-phase 4-wire system on load.

be made by test plugs to facilitate such testing.)* The maintenance of high insulation values should be to the electrical engineer as much a routine matter as the maintenance of lubrication is to the mechanical engineer. The satisfactory flow of lubricant in vital mechanical

* See Reference (17). † *Ibid.*, (18), (19), (20), (21), and (22).

* See Reference (23).

movements is checked by sight gauges, oil gauges, and bearing thermometers, but the corresponding arrangements for checking the satisfactory state of insulation are not so well developed.

A leakage indicator in the main neutral connection of a 3-phase 4-wire supply does not distinguish between a large leak at one point in the network and a multitude of small leaks. The recent emphasis in regulations and elsewhere on leakage currents of the order of 30 milliamps. has encouraged the development of several types of protective switchgear, but for the *prevention* of short-circuits even such leakage trips are inadequate. A weak spot in a piece of insulation may pass less than 1 milliamp. up to the instant when the insulation finally breaks down. In most cases of insulation failure in motor circuits, there is a preliminary period of low insulation value before the final breakdown. In many instances the application of an insulation tester at the main switch each time before the motor is started would give sufficient warning, but the trouble of making such frequent tests would generally be considered more than is worth while, i.e. more than the remote risk of failure justifies. It is commercially necessary that the cost of fitting or applying apparatus for making such a test should be proportionate to the risk to be guarded against. It is not sufficient to test a large group of motor circuits. If the group is tested while the network is dead, the no-volt releases on the motor starters will isolate the motors and motor cables from the test and, even if the difficulties of testing the network while on load for insulation to earth are overcome, the position of faults will not be located by a group test. It will further be necessary to distinguish between leakage currents of the order of 1 milliamp., corresponding to 0·2 megohm on 200 volts, and capacitance currents across the insulation, which may be of higher order (see Fig. 14). Nevertheless, the problem of providing visible indication in each motor circuit (or in selected important motor circuits) of the safe or dangerous insulation value of the insulation in that circuit can be solved (see Fig. 15 on Plate 2), and if the avoidance of short-circuits by very sensitive leakage indication or ultra-sensitive leakage tripping becomes generally desired in motor circuits, the cost can be brought down by further development.

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DISCUSSION BEFORE THE INSTITUTION, 21ST JANUARY, 1937

Mr. H. W. Clothier: I share the author's desire to establish recognized limits to the blocks of power which under fault conditions may be concentrated on parts of low-voltage motor installations. Electricity, like other services, when abused, is likely to turn with a viciousness that is sometimes very harmful. It is therefore necessary to agree upon the economic limits at which its bulk can be conveniently kept under safe control for the several places of its passage and use. Of these places, industrial premises are of particular interest in that the controlling apparatus must come into close proximity to persons, and continuity of process is of economic importance.

I agree that the use of 3 300 volts is desirable for the larger motors. It would be interesting to know the way in which high-rupturing-capacity fuses such as those shown in Fig. 5 have been proved by short-circuit test;

and how their characteristics compare with those of the low-voltage fuses illustrated in the paper.

Failure of contactors due to flashover either to earth or between phases would appear to be a function of the enclosure, and to be a point not always overcome in design. The frequent call upon the back-up fuse protection caused by installing starting gear in too small an enclosure appears not to be sufficiently realized, particularly where built-in starters are concerned.

select a fuse on the basis of its minimum fusing current. For direct-started motors, in general, a fuse having a minimum fusing current equal to the nominal starting current of the motor, usually given as 6 times the normal current, is satisfactory. This allows for any slight errors in estimating or determining the starting current and for the time during which the starting current is maintained.

The limitation of the fault current due to the use of small cables may to a large extent account for the com-

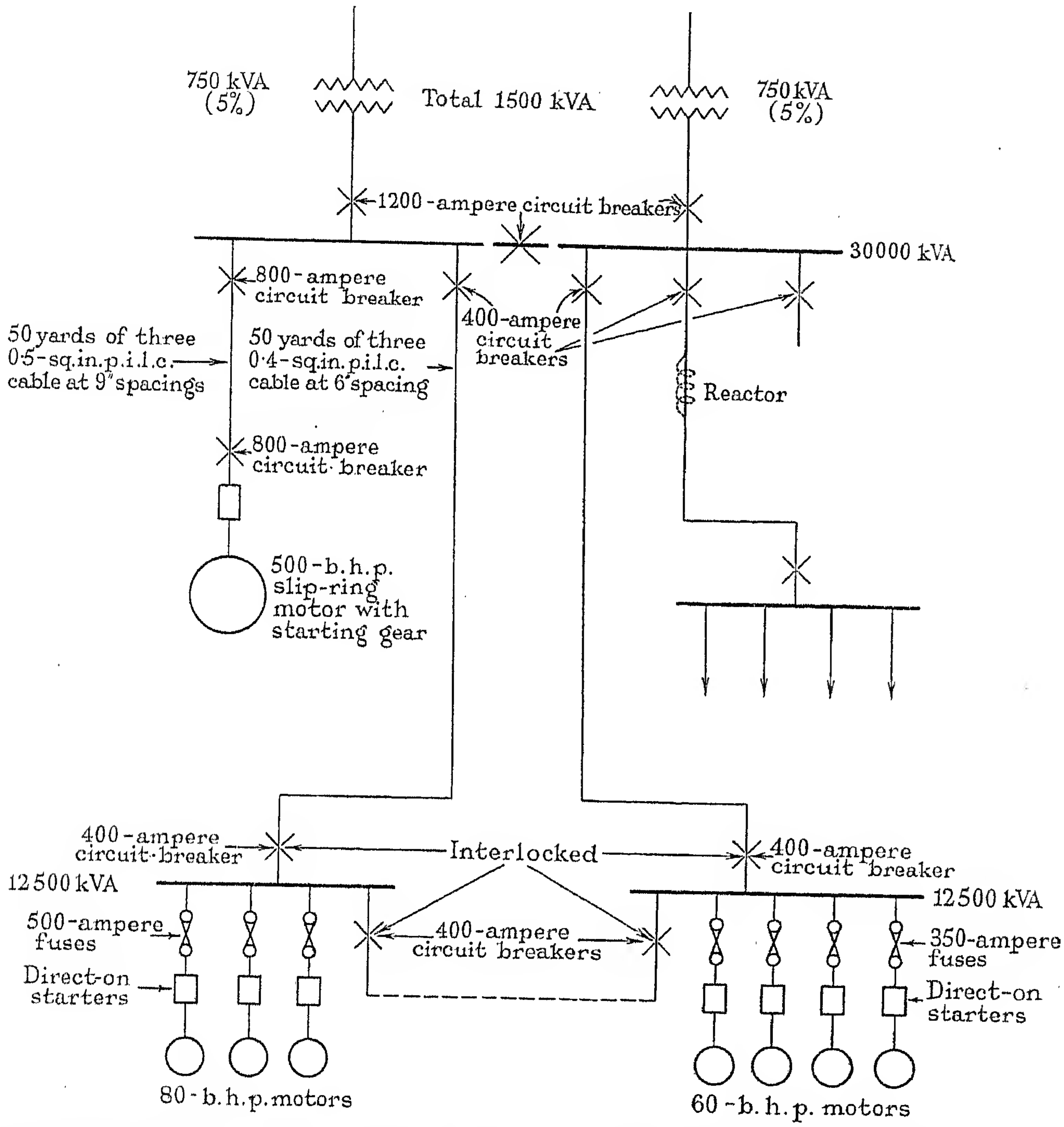


Fig. A.—Suggested layout for a maximum short-circuit capacity of 44 000 amperes at 400 volts, i.e. 30 000kVA, with motor circuits limited to 12 500 kVA either by sectionalizing or by arrangement of main cable impedance.

The fusing of a low-rated thermal trip by a short-circuit current is to be expected where direct heating of the trip is utilized. As the author says, these are more easily damaged than magnetic trips, but it should be pointed out that where low-current series trips are used these are also subject to a limitation of the current they can carry.

The author mentions that fuses having a rating of 3 to $3\frac{1}{2}$ times the normal current rating of the circuit give satisfactory results. He makes no mention of the fusing factor, and it is suggested that it would be better to

paratively few failures of motor-starting gear in service. The author shows the current-limiting effect of small cables; although this reduces the duty on the starting gear, the fact must not be overlooked that should a fault occur at a point near to the distribution gear the limitation due to the cable is practically non-existent, and the full fault current available under such conditions may result in damage to, or even the destruction of, the cable between the distribution gear and the point of the fault.

One of the features of the paper is that starting apparatus is intended for starting the motor and protect-

ing it from overload, but for short-circuit protection of the whole circuit including the starter we must look to the quick-acting fuse and oil circuit-breaker. This leaves a clear-cut field in which to lay down the limits for satisfactory operation of these circuit-breaking devices, and to determine the economic voltage in relation to the quantity of power required.

It may be true that the greatest attention up to now has been given to tests of high-voltage circuit-breakers, but low-voltage circuit-breakers and cartridge fuses have also received attention. Therefore, and notwithstanding the evidence given in Table 3, I suggest that a reasonable economic breaking-capacity limit in close proximity to the power-supply low-voltage terminals at 400 volts is of the order of 30 000 kVA. When stated in terms of the maximum normal output of transformer banks at 5 per cent reactance the limit is 1 500 kVA (say three 500-kVA or two 750-kVA units) using 1 200-ampere circuit-breakers as a maximum. From the main board it would be necessary to feed through sufficient reactance in cables to sub-distribution boards with such division of the loads as to keep the short-circuit in its proximity to, say, 12 500 kVA for fault clearance by high-rupturing-capacity cartridge fuses (Fig. A). The total time for operation of the ordinary circuit-breakers from the energizing of trip coils to final arc extinction would be that corresponding to about 4 or 5 cycles, whereas a cartridge fuse of, say, 300-ampere normal rating clearing on a 12 500-kVA fault would be so speedy as to curtail the damage at the fault anywhere on the circuit, including the starting switch.

Referring to the author's comments on fuse testing (page 152), single-phase tests at full voltage between phases represent the true criterion for maximum severity provided that test circuits are timed to produce a peak of the power-frequency voltage at the instant of melting of the fuse. The author is hardly correct in assuming that the maximum stress on any phase is always produced by repeated 3-phase tests, but it can always be obtained deliberately and consistently by a single-phase test on a single fuse at line voltage, with a suitable timing device.

Whatever the data used on which to base a design or on which to express an opinion on a design, the only safe policy is to prove the performance of the circuit breaker under testing-station conditions where the constants of the circuit can be controlled and low power-factors obtained. For example, the design of arcing contacts may appear to be correct when considered from the point of view of electromagnetic forces, but in low-voltage heavy-current circuit-breakers the arc itself sets up pressure waves, which add to the stresses on the contacts, and it is only by actual tests that the suitability of the design can be proved. The conditions under short-circuit are generally so complex that they do not lend themselves to solution by calculation alone.

Mr. E. A. Reynolds: The author makes out an extraordinarily good case for the high-voltage motor, and suggests using 3 300 volts as the maximum for motors of over 100 h.p. He implies that possibly large motors, such as winding-gear motors, might be run at the higher standard voltages of 11 000 volts. In the area in which I am interested, until recently the transmission voltage was 5 000 volts, and as long as 25 years ago we were installing high-voltage motors for the heavy drives in rolling-mills and factories, and since then the voltage has been raised to 11 000, and the motors have been changed to suit. These motors have involved less trouble and less expense of maintenance than low-voltage motors of the same size, and I cannot see why it is necessary to reduce the voltage to 3 300 volts, because this necessitates another transformer, which in itself helps to reduce the efficiency and also increases the capital outlay.

The author refers to the essential difference between the breaking of d.c. and of a.c. circuits, and I am afraid that the designers of switchgear have not paid sufficient attention to this. Present-day switchgear has been developed on the basis of the experience gained on, and principles involved in, d.c. circuits. The author gives as an example the short-break switch, but he does not carry the principles involved in this switch quite far enough. The ease of breaking associated with it is not due to a mechanically-controlled short break but to the short break itself, which may not be mechanically controlled. What I mean is that if there were a slow-break switch that would only open to a short break over a period of between 1 and 2 cycles, we should have exactly the same effect as that given by a mechanically controlled short break, but the switch might be allowed to continue on and finish as a normal-break switch. This would give the designer an opportunity to provide the necessary speed of closing of the switch, and also a more positive contact when the switch was closed. I think that the design of switchgear will follow these lines in the future, when it is realized that a.c. circuits will automatically break themselves if they are allowed to do so without external interference. Research is necessary to determine how far these slow-break but normal-gap switches can be used on highly inductive circuits, but on comparatively small circuits which are inductive I have found a slow-break switch of this type to be quite satisfactory.

Dr. W. Wilson: The author has referred to the "low-voltage complex" which is responsible for the ordering of so many freak oil circuit-breakers. It seems extraordinary, now that 132 kV is quite a common voltage, that engineers should be straining every nerve to use such low voltages as 3·3 kV, or even 440 volts, when a higher voltage would give a much better arrangement. Even as regards safety, the advantage of the lower voltage is illusory, since 400 volts alternating current is already capable of producing fatal results, while it is recognized that certain faults (e.g. broken overhead conductors) are much less likely to clear themselves by tripping the breaker for low voltages than for high. On the other hand, as Mr. Clothier has said, the use of too low a voltage introduces very considerable difficulties in the design of the breaker. If, for example, the breaking current in a 400-volt switch is compared with that in a grid switch of 132 kV, the former is found to be 330 times as great as the latter for a switch of the same kVA; while the current in a 50 000-kVA switch at 400 volts is over 10 times as great as that in a grid circuit-breaker of $1\frac{1}{2}$ million kVA operating at 132 kV. With the low-voltage switch the contacts have to be much bigger for the same normal kVA, and therefore all the clearances are reduced. In addition, as the author shows, the high breaking capacities often

specified are unnecessary for the simple reason that the reactance and resistance concerned will in general not allow such currents to pass. It is a safe rule, and one which I think will be followed in future, that no switch should be designed to stand a breaking current of more than 44 000 amperes, or a peak making current of more than 110 000 amperes; and this rule will limit the breaking-capacity rating of a 400-volt circuit-breaker to 30 000 kVA.

With regard to overload releases on starters, trouble is continually being caused through these being expected to function as circuit breakers. They are not intended for this purpose, but are put on to guard the motors against overload due to something going wrong with the load or due to improper use, and they should not be required to break more than about 6 times the normal current. Faults in the motor should be cleared by some other device.

Mr. Clothier showed a diagram of a circuit fed by two transformers in parallel, an arrangement which one often finds supplying an industrial load from the grid. In such cases each transformer is usually made large enough to carry the load by itself, the second being provided as a spare. If both of the transformers are left in circuit by mistake or design, the short-circuit capacity is nearly doubled, and the breaking capacity of the switchgear may well be exceeded. Not long ago I had an experience of a very serious breakdown due to this cause, and I should like to ask the author whether he does not think that some kind of interlock should be rendered compulsory to prevent such an occurrence.

He does not mention a saving of which advantage is being increasingly taken at the present day, whereby a single starter is used for a large number of motors—" plural starting " it is called in some cases. In certain paper mills, for example, where a number of beaters using motors of about 300 h.p. are installed, five or seven motors at a time are controlled by one starter. Such machines run all day, but only have to be started once or twice daily. It is very much simpler, cheaper, and more efficient, to have one starter which can start the motors in succession and then hand over the job of protecting them to a pair of contactors with overload relays. Plural starting is particularly useful on board ship*, where up to 25 motors are controlled by means of one starter. The motors need not be of the same, or even of nearly the same, horse-power.

The author compares thermal trips unfavourably with mechanical relays, and states that, if a large overload occurs, the heating element is in danger of burning out before the trip gear will clear. While it is true that if bimetal strips are designed on too flimsy a scale that may happen, it should be realized that the electromagnetic type is also susceptible to the same sort of disaster. I have known cases where quite robust electromagnetic coils have suffered damage through a sudden overload burning them or distorting them mechanically before the trip could function. Thermal trips of robust design are at least as reliable as the electromagnetic type. Considerable advances have been made within recent years in the production of bimetal, and there is still less excuse for making the elements excessively thin than there ever was.

* See *Journal I.E.E.*, 1935, vol. 76, p. 241.

The figures quoted by the author from B.S.S. No. 168—1936 are an example of confused wording. Clause 44, which states that the period for which motors can be required to stand twice normal torque is 15 sec., is intended to specify a mechanical test. I showed in a recent article* that the time for which a motor will stand twice normal torque is fixed by two provisions already in the Specification, namely that (*a*) it has to stand normal load continuously for an infinite time, and (*b*) it has to stand 1·25 times normal load for 2 hours, to take the largest category as an example. From this it can be deduced that the time for which it will stand twice normal torque is 5·2 minutes. It is a great pity that the matter is not made clearer in the Specification.

Mr. E. H. B. Martin: A good deal of trouble may be set up should a small starter or contactor open under short-circuit conditions. In view of this it is necessary to ensure that contactor gear used for motor control is prevented from opening under those conditions. With the use of squirrel-cage motors the thermal overload trip is becoming almost universal, owing to its ability to integrate over a period of time the heating characteristics of the current, and this type of relay provides a finite time-delay however great the current becomes. With a separately heated thermal relay it is usually found that the minimum time-lag is of the order of a second or so, compared with the fraction of a second typical of the dashpot relay. If the fuse or circuit breaker is properly proportioned to the duty, then with this type of relay it is certain that a fault in the motor or wiring will be cleared by the switchgear, as it should be.

A point which the author has made more plain in his verbal summary than in the paper is the enormous difference which power factor makes to the rupturing capacity of an a.c. contactor. For motor-control purposes the true rupturing capacity of an a.c. contactor can only be determined by a large number of tests at low power factor.

Mr. L. Gosland: In discussing short-circuit ratings of circuit breakers the author states that the reactance of quite short leads between a transformer and, say, a 440-volt breaker is often of great importance in reducing the short-circuit kVA at the terminals of the circuit breaker. He instances that a calculated value of 15 000 kVA at the transformer terminal was reduced to 10 000 kVA at the circuit breaker by the reactance of quite short leads. While this is quite typical of many cases, there is perhaps some danger that the idea may get into circulation that a similar reduction must always occur.

It should be remembered that the limitation of the short-circuit kVA is obtained at the expense of increased supply reactance, i.e. of increased voltage-drop from no load to full load, and that most often it is possible by suitable layout of plant and careful attention to the arrangement of conductors to keep the short-circuit kVA at the switch nearly as great as at the transformer, with correspondingly good regulation at the busbars.

It ought thus to be a question to be decided for each case on its merits, whether one was going to have,

* *World Power*, 1936, vol. 25, p. 8.

say, a 15 000-kVA switch, with good regulation at the busbars, or, say, a 10 000-kVA switch with rather worse regulation.

With regard to fuses, in Fig. 10 the author shows an oscillogram of a 500-amp. cartridge fuse clearing a very heavy short-circuit in a most exemplary manner, with very little over-voltage, and on the other hand he shows in Fig. 13 an oscillogram of a 100-amp. rewireable fuse failing to clear a short-circuit and giving rise to tremendous over-voltages (which, as is indicated, are liable to damage insulation elsewhere on the system).

No one would, of course, suggest on this evidence alone that rewireable fuses are always less satisfactory than cartridge fuses, but it is clear that some dividing line must be drawn between the types of fuses which, on a given circuit, *will* and *will not* set up over-voltages, and between types of circuits which *are* and *are not* subject to over-voltages with certain types of fuses.

This is a subject on which very little information is now available, and on which the E.R.A. are now conducting an investigation: it would be very useful if any existing evidence bearing on this subject could be communicated to them.

Mr. D. St. A. Butcher: I should like to ask for a line of demarcation to be drawn between the circuit breaker, the fuse switch, and the motor control gear proper. The modern practice in large factories is for the low-voltage supply from the transformer to be taken through a circuit breaker direct to the sub-distribution busbars, this sub-distribution being carried out by fuse switches, and the motor itself being manipulated by control gear.

In the fuse switch the non-rewireable cartridge fuse is now generally employed and, as these fuses have been proved to be capable of rupturing a circuit of 25 000 kVA and upwards, it is quite unnecessary to attempt to reduce the rupturing capacity of the circuits to a region of 12 500 kVA.

The author states that the cartridge fuse ruptures the circuit in between 1/1000th and 1/100th part of a second, and as it is impossible for any piece of mechanical apparatus, such as a contactor, to separate its contacts in so short a time as this, it is not possible for the circuit to be ruptured under short-circuit conditions in the motor starter, because this fuse will have blown before the current-carrying parts separate. The function of the control gear is to manipulate the motor, and it will contain overload devices to take care of perhaps 5, 6, or 7 times full-load current, but currents in excess of these should not enter into the calculation of modern control-gear design.

With regard to thermal overload trips, a device of this sort has been brought to my notice in the form of a bimetal thermal strip, which is built into the motor. It is far better to measure the actual heating-up of the motor itself, than to try to control its temperature by means of the amount of current passing through a bimetal strip in the control gear.

Mr. A. Morgan (London): I am somewhat surprised at the neglect of mercury fuses in this country, and I should like to know why they are not discussed in the paper.

Mr. W. E. Highfield: Several speakers have advocated raising the voltage of certain motors in order to decrease the short-circuit kVA on the switchgear. The voltage at which a motor may be satisfactory is decided almost entirely by mechanical considerations. If the copper section of the armature conductors is of such small dimensions that insulation cannot be wrapped round it without injury to the insulation, or the end windings have not sufficient mechanical strength to withstand the shocks of ordinary usage, then the voltage is too high. The electrical difficulties due to raising the voltage can almost always be met.

Mr. P. J. Higgs (*communicated*): The paper gives the idea throughout that, regarding the rupturing capacity of l.t. distribution equipment, satisfactory operation will be obtained until some final high value of current is reached. In carrying out short-circuit tests on cartridge fuses at the N.P.L. (Teddington) with direct current I have found in several instances that a fuse may clear quite satisfactorily a high current yet fail at a much smaller current, e.g. clear at 9 000 amperes but fail at 1 500 amperes, for similar voltage conditions. It would be of interest to know whether any such phenomenon has been found in short-circuit tests with alternating current. If it has, it would seem to require particular attention since heavy overloads may occur much more frequently in practice than severe short-circuits, as appears to be indicated by the references in the paper to the mechanism of insulation breakdown.

The correlation, if any, between a.c. and d.c. short-circuit testing is a subject of some importance and it would be interesting to know whether there is any relevant technical information available. Tests with alternating current can be very variable and, in this respect, somewhat unreliable, whereas tests with direct current are fairly consistent. Research on the subject, which seems to be called for, may indicate that d.c. testing provides a reliable means of "proving" circuit-breaking devices for use in either a.c. or d.c. circuits and, if in the former, at voltages and currents greatly in excess of those of the d.c. test conditions. Perhaps it is not quite exact to refer Table 2 to B.S.S. No. 88—1931, since the Specification deals—for rupturing capacity only—with d.c. tests at 260 volts. In Fig. 13 the test voltage has apparently been omitted.

Mr. B. H. Leeson (*communicated*): Table 2 gives the short-circuit current requirements specified for fuses in accordance with B.S.S. No. 88—1931. This Specification applies only to semi-enclosed fuses up to 100 amperes rated carrying current at 250 volts, and the need has long been recognized for a specification of much wider scope which will include high-rupturing-capacity type cartridge fuses. With this aim in view, B.S.S. No. 88 is at present being revised to cover fuses suitable for the following types of duty: (*a*) House service, (*b*) light industrial, (*c*) power station. It will be seen from Table 2 that the short-circuit current with which the corresponding fuses must deal increases as the normal rating of the fuse increases. It is now recognized that this classification is quite wrong and that the short-circuit current which a fuse may be called upon to clear depends upon the "vicinity" or "prospective" short-circuit current at a location on a network, and this is not related to the

normal rating of the fuse. For example, the rupturing capacity of a 15-amp. fuse for industrial service must be just as great as that of a 100-amp. fuse for the same duty. Thus in the revised draft of B.S.S. No. 88, now in preparation, the short-circuit requirements are divided into four categories of duty as shown in Table A, and each category applies to a complete range of normal current ratings.

Table A

Category of duty	Maximum "prospective" current (r.m.s. amps.)	Representative category of duty
1	1 000	House service
2	4 000	Light industrial
3	16 500	Heavy industrial
4	33 000	Power station

I agree that under 3-phase short-circuit conditions on a 400-volt 3-phase system the condition may arise when two fuses may be required to clear, each with the full 400 volts across their terminals. This will take place if two fuses melt before the third, since the third fuse then becomes practically a link in its phase and each of the other two fuses is in effect operating as a single-phase fuse at the full line voltage. Such a condition represents the maximum voltage severity of fuses in 3-phase circuits. In spite of the fact that this severe condition often arises in 3-phase operations of fuses, it must be pointed out that 3-phase tests by no means necessarily reproduce these conditions. In addition to the extremes of voltage severity obtained, practically any intermediate voltage severity may be encountered in the ordinary course of 3-phase testing. In order to avoid this inconsistency of 3-phase testing the best method of test is a single-phase test on a single fuse at the full line voltage, because this reproduces deliberately and consistently the necessary voltage severity. In addition, any possible asymmetry effects can be covered by including in the test circuit a timing device arranged to close the short-circuit, so that, at the instant when the fuse melts, the power-frequency voltage wave will be rising towards its peak value.

[The author's reply to this discussion will be found on page 173.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 18TH JANUARY, 1937

Mr. O. C. Waygood: While the practice of grouping motors and starters for dealing with power distribution in a large building tends to increase the capital outlay on this installation, it is justified by way of reduced maintenance costs.

Co-operation is rightly stressed in the paper. With all the facilities available to-day for getting together it hardly seems credible that there is so little effort of co-ordination amongst those engaged in solving technical problems.

There are many instances where motors are used in order to reduce running costs and to deal with output; manufacturers go to endless trouble in building such motors into particular pieces of equipment, and lose sight of the fact that, no matter how well designed or efficient the motor is, it cannot function without the control gear. In consequence many a piece of very good equipment is spoilt.

The fitting of isolators interlocked with starters is a point which should, in the interests of safety, become an established fact.

Mr. D. K. Coldwell: Group starters are not quite convenient for boiler-house auxiliaries, where the induced-draught fans are on the roof and the forced-draught fans in the basement. This case calls for a grouping of remote controls for remote automatic contactor panels. Also I do not agree with ring-main supply for a boiler house, as on this system one fault upsets all the boilers. I consider the tee system with alternative supplies to be the proper one.

The author gives a figure of 1 500 amps. as the capacity of the largest satisfactory switch; I think this should be 2 500 amps., as switches of this value can work satisfactorily without attention, and are not too expensive.

He recommends a separate transformer for each boiler; this may be applicable to extremely large units, but for the ordinary rating of boilers for industrial plants (60 000 to 150 000 lb. per hour) I am afraid there would be little room for anything else than the transformers and associated switchgear in the average industrial station.

I utilize thermal overloads up to $7\frac{1}{2}$ h.p. and find them satisfactory, but for higher values they are unsatisfactory, even with protective fuses for dealing with short-circuits. I have used cartridge fuses for about 15 years and have found them so satisfactory that I would not recommend anything else.

I do not agree that 500 kW should be the largest transformer for distribution purposes; the figure for works distribution is three to four times this size. As regards rupturing capacity, a large number of manufacturers have already tested out high-voltage but not low-voltage switchgear. The tendency in the past has been to increase the speed of operation, but the experience gained on high-voltage testing is moving everyone in the opposite direction, so that current starvation does not surge the system.

Mr. E. G. Taylor: B.S.S. No. 587—1935, Clause 72, calls for starters to be fitted with an overcurrent release capable of breaking 6 times the normal full-load current of the a.c. motor it controls. This appears to be insufficient, as the normal short-circuit current of squirrel-cage machines may in special cases reach 10 times full-load current. For some years past, engineers have looked upon a motor starter or motor controlling device as a circuit breaker; but such devices are primarily intended for starting and stopping motors, speed regulation, and providing the means for protecting the motor against the failure of supply or overload resulting from causes which may generally be stated to be due to some mechani-

cal defect in the drive or driven apparatus but not due to the development of an electrical fault, e.g. a short-circuit in the machine or cabling beyond the starter or controller.

The author advocates the use of high-rupturing-capacity fuses to take care of these electrical faults, but, where such are used with a combination of overload relays on the starters, difficulties may occur due to the time-delay action of the fuses, as obviously the fuses offer no protection if the overload relay on the starter operates first. It therefore appears essential for the circuit to be fused so that the instantaneous fusing current does not exceed 6 times full-load current, and preferably time-lags should always be fitted to the overloads on the starters. Where it is desired to control a group of motors from a single set of fuses it appears impossible to obtain proper protection by this means, as it is obvious that the instantaneous tripping current of the fuses should not exceed 6 times the full-load current of the smallest motor on the circuit. It is quite common practice in works installations to group the small motors in this way, and the scheme as such appears to be undesirable.

Mr. C. T. Scarf: I should like to make one or two remarks about the control of a.c. arcs. Some years ago I had to design a 300-amp. a.c. contactor; at the time there was a good deal of discussion amongst engineers as to the necessity for blow-outs on a.c. contactors, and it was decided to try out our new contactor with arc shields only. The performance of the contactor was tested by connecting it in circuit with the stator of a 300-h.p. 625-volt motor, the slip-rings of which were connected to suitable resistances and the rotor locked. Everything appeared to be satisfactory and the arc on breaking was, as the author has suggested, very small. Unfortunately when the contactor was installed with its motor on site it was found to be quite incapable of handling the circuit owing to the large frame size of the machine. Blow-out coils were fitted, the contactor being otherwise unaltered, and it was then perfectly successful. This suggests that blow-out coils cannot be omitted from a.c. contactors without very careful consideration of the circuit conditions.

With regard to the question of arc boxes with narrow slits, I should like to know the author's opinion of the use of such boxes when very frequent arc-breaking takes place; one would imagine that the sides of the boxes would heat up and the boxes would lose their efficiency. Another point in connection with such arc boxes concerns the formation of corrosive gases. We have made some rather elaborate tests to determine the relationship which exists between the shape of the aperture and the amount of such gases formed. By suitably proportioning the box we have been able to reduce the amount of such gases to nearly one-quarter of what it is with an ordinary open-arc type.

Referring to the author's statement that air-break contactors are superior to oil-break contactors for dealing with frequent switching operations, does he think that the burning which takes place under oil can be reduced by suitable contactor design?

Until comparatively recently "overload protection" took the form of a magnetic relay which had to function on either steady overloads or fault currents. Now that the required breaking capacity is often difficult to obtain with small starting switches, high-rupturing-capacity fuses are used to take care of fault currents, leaving the relay to deal with normal overloads only. The question then arises whether we should continue to use magnetic relays in preference to the thermal type. There is no doubt that theoretically the thermal relay is superior, but it lends itself to cheap and unreliable construction and as a result has been somewhat discountenanced. Furthermore, the thermal type of relay is inherently difficult to set and test precisely, and it is therefore difficult to convince inspecting engineers of its excellence. It would be helpful if the author would give us his views on the relative merits of thermal and magnetic overload relays used in connection with fuses. It would also be interesting to know whether he has found it necessary to use larger starters than usual in order to carry the fault current safely until the fuse has cleared the circuit. This particularly applies to small apparatus of, say, 25 amps. capacity.

The author suggests that special testing plant for determining rupturing capacity is not necessary, but I think it is a great advantage to have access to a properly laid-out testing station where tests can be made rapidly and accurately. Power factor, which is of vital importance, is then under complete control, and oscillograph records are available a few minutes after each test, so that the need for repeating any particular test is immediately apparent. The use of a storage battery for making such tests is to be deprecated, as the results cannot be relied upon to be comparable with those obtained in practice.

[The author's reply to this discussion will be found on page 173.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 2ND FEBRUARY, 1937

Mr. W. Kidd: The author shows that it is altogether wrong to arrange protective devices for either a motor or any other piece of apparatus without taking into consideration other equipment and circuits. The whole of the circuit-interrupting devices which are in series ought to be set down on a diagram and the protective gear of the system considered as a whole. Unless that is done it is quite impossible to design a good distribution circuit, and what happens is that the interrupting devices do not operate in the correct sequence. For example, when starting a fan it may be that, owing to conditions which occur in practice, the dampers are not perfectly closed, with the result that the motor does not accelerate quickly enough or even attain the correct change-over speed. In such cases a high-voltage circuit breaker may open before any of the low-voltage protective devices operate. The result, of course, is that interruption of other services is caused, a thing an engineer should design circuits to avoid.

I hope the switchgear manufacturers will make no attempt to popularize the use of a time delay in the no-volt release. If widely used it will produce some

rather undesirable effects on a supply system, and we should like to see it reserved for extremely special cases.

The author refers to the short-circuit kVA which may occur on low-voltage equipment, and mentions a figure of 20 000 kVA. I find that on a densely loaded urban system it is quite possible to get 30 000 kVA in the substations, but, as is shown in the paper, the impedance of the cable system very rapidly diminishes the short-circuit kVA. In the case of the urban system I have mentioned the addition of 100 yards of ordinary distributor will reduce the fault kVA to 15 000. In any normal case—taking into account the service cable —there must be few consumers who get more than 8 000 kVA at their service terminals; the majority of consumers get much less.

I support the author in his contention that something like 1 500 amps. is the largest normal current one should attempt to deal with with low-voltage equipment. I find that 2 000-amp. switches cannot conveniently be manually operated. In this area we have tried to keep down the current by limiting our distribution transformers to about 1 000 kVA capacity. I think 1 500-kVA transformers for 400 volts are the largest size one should attempt to use. Recently, however, I had to deal with some 400-volt switchboards where we needed circuits for 2 000-kVA apparatus; in such cases busbars of several square inches section are necessary.

It is not always convenient or economically possible to use the higher-voltage motors which the author suggests, especially when extending existing installations. I agree with him that a more extensive use of higher-voltage motors will be made in the future—certainly of 3 000-volt motors—but, as the distribution is usually carried out at 6 000 to 11 000 volts, I should like to know what the experience has been with motors of 100 h.p. and over made for these higher voltages. One must not forget that machines of 100 kW for 6 000 and 11 000 volts have been used in distribution work for 20 years and over, and have given entirely satisfactory service. Perhaps one would argue that in industrial installations the conditions (cleanliness, dryness, etc.) are not as good as in substations.

My operating friends are inclined to favour the oil-immersed circuit breaker rather than the contactor type of gear for motor starters in power stations, but I find on investigation that there is not such a strong argument for the former as they make out. The matter depends largely on the circumstances in which one is using the gear. Our experience shows that if some small trouble develops the operating staff can more readily deal with the circuit breaker than with the contactor type, with its numerous coils and relays. I do not want to put this forward as an argument against the contactor gear, because I believe it will be used much more in the future, and I am making more use of it now than of the oil-immersed gear for power-station motor starters. When frequent operation is necessary contactor gear is the only reasonable proposition. With the manually operated star/delta starter one is dependent on the judgment of an unskilled operator, who relies either on noise or on his ammeter, for the decision as to when the change-over should be made. That is not likely to lead to any difficulties with small motors, but with large motors it has very often led to very bad change-overs and to interference on other circuits. There, I think, the contactor type of gear scores, because it takes the matter entirely out of the hands of the operator.

The author refers to the expense incurred in using motor starters in series with oil circuit-breakers on the auxiliary switchboard. I got over that difficulty a good while ago, for large motors which are infrequently started, by using the switch on the auxiliary board as the motor starter (remote electrically controlled). This arrangement has proved quite economical and very clean and neat.

The author showed a number of diagrams on the screen which I should like to see incorporated in the paper, particularly the one dealing with current transformers, which illustrates the necessity for adequate thermal and mechanical properties.

I suggest that when purchasing motor starting gear much greater attention should be paid to the rating of the auto-transformers on the larger motor circuits. Auto-transformers of small capacity are frequently offered on account of low price and lack of understanding of the service conditions. The starting conditions in service are always much more onerous than they are in theory.

Mr. S. Farrer: As the author states, the rupturing capacity of low-voltage industrial circuit-breakers has received insufficient attention in the past. Some manufacturers have now recognized the importance of adequate capability under short-circuit conditions and are developing and testing their low-voltage industrial breakers in a manner similar to that adopted for high-voltage circuit breakers. There are, however, practical limits to the amounts of short-circuit MVA which can be handled economically on low-voltage systems. The real difficulty in low-voltage circuit-breaking is, of course, the magnitude of the current; expressing the short-circuit conditions in terms of current would give a more useful conception of the severity. The value of 25 MVA sounds very innocuous, but if it occurs on a 440-volt system the currents to be broken are 30 000 to 40 000 amps., and these constitute a serious problem. The peak value of corresponding inrush currents may be nearly 100 000 amps., and a large circuit breaker of heavy normal current may experience on its cross-bar a force of the order of 1 ton at this value. The magnetic forces inside the circuit breaker are very large in comparison with the normal operating forces, and for this reason constitute a special problem to the designer of gear which must be safe under those conditions. The difficulty of calculations of the forces, together with the complication of arc phenomena, render a check by short-circuit tests essential.

A further point, not generally appreciated, in connection with these heavy values of short-circuit current at low voltage may be understood by comparing a heavy 6 600-volt circuit breaker of 500 MVA breaking-capacity rating (i.e. 43 800 amps.) with a 440-volt breaker of the same breaking current, rated at 33 MVA. In comparing the severity of the duty performed by circuit breakers we should consider the arc energy as well as the electromagnetic forces. The arc length is also important. With 3-phase breakers the arc length is not necessarily reduced to less than 2 half-cycles, and in many large breakers

clearing faults at 440 volts the arc length will be of this order. If that same current is being broken in a 6·6-kV breaker it may run to 6 half-cycles, but in a breaker with arc-control device it will not amount to more than 2 or 4 half-cycles, at the most. In other words, the arc energy, being dependent on the current and arc length, is by no means proportionately smaller in the 440-volt breaker than in a 6 600-volt breaker. The problem of tank pressures and design for low-voltage breakers is therefore very important, and tanks mechanically weak or of cast iron may be a source of trouble.

In the layout of a low-voltage system one has to bear in mind that the effect of current is a real problem in regard to the busbar connections and circuit breakers. As stated in the paper, systems should be sectionalized if necessary to keep both normal and possible fault currents to reasonable limits; failing this, a rearrangement using an increased system voltage is desirable and may actually be cheaper to install.

The author gives an indication of the short times in which high-rupturing-capacity fuses can operate; whenever figures of a few thousandths of a second are quoted for fault clearance by means of a fuse the effect of the fuse in cutting off the current and thereby producing overvoltages should also be considered. Rapid current cut-off can cause dangerous voltages and flashover or faults in the system insulation. In the case of circuit breakers the current dies off comparatively slowly and tends to be extinguished at a current zero in the a.c. wave. Thus, although the current interruption takes a longer time, the tendency to overvoltage effects is minimized.

I should like to draw attention to the fact that some ordinary industrial oil circuit-breakers, without time-lag, will operate very quickly. Oscillograms taken in recent short-circuit tests show that currents of 3 to 13 000 amps. were interrupted with arcing times of about 1 half-cycle, the total duration of the short-circuit in both break and make/break shots being up to 2 half-cycles or 0·02 sec.

Mr. R. M. L. Evans: On page 147 the author deals with the means of giving the operator the facility of shutting down the motor under emergency conditions, and at the same time of protecting himself against anyone starting the motor again from another position. This can be done by incorporating a push button with normally-open and normally-closed contacts, the former being connected in the closing-coil circuit of the mechanically latched contactor and the latter in the shunt trip circuit. If the push button is then made self-retaining by means of a bayonet locking device or other means, the operator can work in safety on the motor. Means must be provided, in the form of an auxiliary switch on the contactor, for de-energizing the shunt trip unless this be continuously rated. It is still questionable, however, whether the Home Office Regulations would be met by this. As regards the idea of an electrically interlocked isolator close to the motor (page 147), there is a danger that in emergency conditions the operator may open the switch very rapidly and possibly race the contactor. A mechanical slow-motion device will overcome this trouble.

The author compares the switching of 3 300-volt and 400-volt motors of 300 h.p., the latter having a full-load current of 750 amps. The 400-volt motor seems to suffer unduly in efficiency and power factor. I think a reputable motor manufacturer could supply a similar machine having a load current nearer 400 amps., and at this figure of current the comparison would not be so disadvantageous to the 400-volt motor. I am, however, in favour of high-voltage motors, if only on the ground that they involve inherent higher rupturing capacity of the circuit.

The author's attempt to make out a case in favour of the high-voltage motor on the basis of standstill current (see page 147) is not fair to the low-voltage motor, as the voltage for which the machine is wound has little effect on the starting current. The starting current (100 amps.) of the example suggests a special design (a high-reactance rotor, probably), and one would estimate that the torque afforded would be of the order of one-third full load or up to one-half full load using a high-impedance rotor. My point is, however, that this could be achieved equally well on a machine of, say, 400 volts.

Let us consider the low-voltage boiler-house layout indicated by the author at the bottom of page 147. The induced-draught fans, forced-draught fans, secondary-air fans, and stokers, will be regarded by the boiler-house engineer as essential services. He will desire these motors to stay in circuit under any circumstances, deeming the service more important than the motor. It follows from this that the control gear will be non-automatic and, if contactors are used for remote control, mechanical latches will be required. On a voltage dip lasting some seconds, unless a delayed-action under-voltage release is incorporated, all motors must restart direct across the line on the resumption of voltage. The transformer capacity and reactance are thus fixed, and it remains to protect against faults. Motors are becoming so large in modern installations that, with aggravation from alternative supplies or ring mains, as illustrated in Fig. 4, the power liberated under fault conditions is alarming, and it is becoming increasingly difficult to give adequate protection.

The motor starting torque afforded by the example on page 147 is ample for fans using a high-reactance rotor, but the extra torque afforded by a high-impedance rotor can be usefully taken advantage of to allow for a drop in volts while starting simultaneously or, if desirable, to achieve more rapid acceleration. I think the station engineer ought to collaborate more closely with the fan manufacturer and the control-gear manufacturer in order to evolve more favourable designs. He should specify that motors should have starting torques as low as the fan makers will accept, and high-impedance rotors should be incorporated to reduce the corresponding starting current to the lowest minimum practicable, even though it involves a small sacrifice in power factor. The tendency to specify motors to cope with boiler overload should be curbed and more use made of motor overload capacity so as to keep down the size and consequently the transformer capacity.

In this respect the use of delayed action under voltage-releases is worth considering. By this means a time-lag is afforded such that if the voltage failure is of sufficient duration to allow the motors to decelerate appreciably the motors are disconnected and only a normal restart

need be legislated for. Additionally, methods of starting other than direct across the line can be used in these circumstances, with consequent reduction of transformer capacity and fault currents.

Referring to Fig. 5, the vulnerable part of the arrangement shown comprises the busbars, isolator, and connections up to the fuses. Careful design and adequate margins of rigidity are needed to deal with electromagnetic stresses and heating of heavy fault through-currents. Switchgear clearances are necessary, as well as adequate spacing of the contacts of the isolator and locking of its mechanical gear. It is probable that compound filling of the busbar chambers is the best arrangement.

I think it is misleading to introduce consideration of the micro-gap switch (page 149) into the paper, as this device is more of academic interest than practical use. It is only of service on a resistance load, i.e. at power factors very near unity. A trial of one of these switches with a motor load will immediately afford proof that a longer break is essential. A blow-out is almost always desirable, even if only as an additional margin of safety. The only exception is rotor circuits, where blow-outs may generally be omitted because the contacts are only inserting resistance and the arc voltage is low.

The effect of power factor on arc behaviour is very remarkable. A contactor that will deal easily with a slip-ring motor over-current of 3 times full load has been known repeatedly to fail to clear when the same motor is inched at standstill with a high external resistance in the rotor circuit. This is purely due to the low power factor. In this condition the blow-out efficiency is much reduced; the arc becomes flaring and flame-like, and the contacts cannot absorb the heat generated. A very powerful blow-out is required to deal with this arc. Further research is needed on low-power-factor arcs.

On page 150 the author discusses oil-immersed and air-break gear. I am surprised that sludging of the oil in the former in frequent service is not mentioned. This is generally regarded as the cause of the excessive contact-burning that follows.

It is becoming common practice for boiler-house and other power-station auxiliaries which are regarded as essential services to rely upon high-rupturing-capacity fuses for the protection of the individual motor circuit. In these conditions trouble is sometimes experienced through failure of one fuse causing single-phasing of the motor and eventual burn-out. With fans and pumps the speed will drop until a point is reached where the torque afforded on single-phase balances that required by the load. This value may be of the order of 50–60 per cent full-load torque, and the drop in speed of the fan is not very great. If the drive is over-motored the pull-out torque may be sufficient to enable the motor to carry on with a drop in speed of only 10–15 per cent. The current in the uninterrupted phases is of the order of twice full-load current, and unless the fall in speed is quickly noticed a burn-out will soon follow. A phase-balance relay is used to protect against this. This comprises an induction-pattern element energized by current coils from two phases. An additional closed-loop winding and a shading loop produce fluxes 120° apart under normal conditions, the torque holding the contacts closed, but the opening of one phase or the reversal of the phase rotation reverses the torque and opens the contacts.

I am sorry the author makes no mention of the design of current transformers or overcurrent coils in connection with the electromagnetic forces under fault conditions. Four factors have to be taken into account, namely (1) temperature-rise, (2) bursting stresses, (3) breakdown between turns, (4) end thrust along the axis of the coil. As regards (1), B.S.S. No. 81—1936 specifies a temperature-rise of 200 deg. C. in 0·5 sec. at 150 000 amps. per sq. in. It should be noted that the current density varies inversely as the square root of the time. Turning to (2), it is not commonly realized that at 36 000 amps. the stresses on a 400-amp. direct-connected coil are measurable in tons. In connection with (3) I would point out that on fault currents the volts per turn are very high, and therefore very carefully designed insulation is required. As regards (4), this crushes the insulation of the end turn and causes breakdowns here. All the insulation must necessarily have elastic properties to allow for movement, and these properties must not disappear through hardening with age.

I shall be glad of an explanation of how the figure of 10 000 kW for arc energy given at the bottom of page 153 is arrived at. Are these figures not misleading, as the arc energy may vary in each of 20 or 30 tests? In any case, the recovery voltage is not mentioned.

Mr. J. M. Gillespie: I am surprised that the author should suggest that contactors are less robust than circuit breakers, as switchgear designers tell me that where frequent operation is required contactors are preferable to circuit breakers.

In the illustrations of the control panels the cubicles all appear to be of the solid-back type. One of the great advantages of mounting control gear in cubicles is that there is access to the back for inspection and rapid tracing of faults. This has a bearing on another point to which the author refers, namely the paramount importance of continuity of supply in many installations. I recently had an opportunity of inspecting a plant where there was a loss of £300 for every hour the plant was shut down. The same installation bore out another point made earlier in the paper—the desirability of unified choice of control gear. In this case the motors and control gear had been supplied by the makers of the various machines and ordered by them from the manufacturer without reference to their suitability for this particular plant. They were a very mixed lot, some from this country, some from America, and some from the Continent. The result was that some first-class equipment was being controlled by flimsy air-break switches. One of these was equally responsible with a heavy 150 000-kVA high-voltage switch for the continuity of supply to the plant. I need hardly say the former was thrown out.

Another interesting part of the paper concerns the mechanism of arc-breaking. The author's photographic record (Fig. 12, Plate 2) of the breaking of an arc on a contactor gives more information than could be gained by watching many thousands of operations. The equipment required for detailed research into rupturing capacity of switches includes oscillographs containing many elements, and these are far too expensive and compli-

cated to be rigged up for each particular test. To make a comprehensive range of tests really requires not only a designer of switchgear but a specialist in testing switchgear.

The flare of, and arc, produced by the addition of a blow-out coil when breaking a comparatively high-power-factor alternating current seems at first sight to be rather appalling. On the other hand, we have all seen the effect—in reducing the flare of an arc—of improving and increasing the magnetic flux. I have seen the same load broken before and after the field strength was doubled, and there was no doubt as to the improvement. In the first case the arc (3 000 volts, 500 amps.) came out 2 ft. from the contacts, but after the strength of the field had been doubled the arc length was a matter of, at the most, inches.

Mr. G. T. Allcock: The author makes a strong case for using 3 300-volt motors for drives of over 100 h.p. on large installations, but experience on change-over from d.c. to a.c. supply shows that there will frequently be circumstances that favour the exclusive use of 400 volts as a distribution voltage. The two following cases, which justify special treatment on account of their size, illustrate this point.

A newspaper printing office with a connected load of 5 400 h.p. had twenty 150-h.p. drives installed in the main machine rooms. In the circumstances 3 300-volt distribution seemed desirable, since the machine rooms were a considerable distance from the only possible substation site, and the number and cost of distribution cables would be a serious embarrassment at 400 volts. The firm, however, decided to make change-over the opportunity for adopting unit drive, and in place of the larger machines are now using eighty 40-h.p. variable-speed commutator motors. Thus the motors had, in any case, to be wound for 400 volts, and since there was no space available in either machine room for a subsidiary substation the distribution also had to be at 400 volts. There was therefore no way of avoiding what to a switchgear engineer is no doubt a special and undesirable equipment—a main switchboard of 40 000 kVA rupturing capacity operating at 400 volts, consisting of two 4 000-amp. interlocked incoming breakers (one as standby) and several outgoing 600-amp. breakers.

In the second case, of an engineering works with a connected load of 3 500 h.p., all the motors are used for individual drive on machine tools and show the high diversity usual under such conditions. If the larger motors had been connected to a 3 300-volt system it would not have been possible to decrease the size of the 400-volt cables appreciably, since the value of the diversity would then have been to a great extent lost. Moreover, the larger motors were so scattered that it would have been necessary to cover nearly half the works with the 3 300-volt distribution system. The distribution cables from the substation were taken from 350-amp. and 500-amp. breakers at 400 volts, while on the incoming side of the substation switchboard a 2 500-amp. isolating switch was used instead of a breaker. The circuit breaker on the high-voltage side of the transformer was thus relied on to clear a busbar fault on the low-voltage board or for shutting off supply in case of emergency. The rupturing capacity necessary on this board was 30 000 kVA, and the board was built up of circuit breakers of reasonable size. Thus in this case 400-volt distribution introduced no serious difficulties, and there seemed little justification for adding to the cost by putting the larger motors on 3 300 volts.

Whether these two cases, or the boiler-house case mentioned by the author, are the more representative, there will undoubtedly be many cases for which switchgear designers are asked to quote for 400-volt boards of large carrying capacity. The possibility of using 3 300-volt motors on certain installations does not make it any less desirable that heavy low-voltage circuit breakers of high rupturing capacity should be developed and perfected.

The increasing use of contactor motor starters, to which the author draws attention, is a development that should please electricity supply undertakings. From the point of view of limiting motor starting current, the hand-operated star/delta starter is not altogether satisfactory, since it depends on the patience of the operator in allowing time for the motor to come up to speed on star. The wide adoption of contactor starters with automatic time-delay between star and delta on large motors should help considerably in maintaining good mains voltage regulation.

Mr. S. R. Mellonie: Dealing with the remote control of contactors, the author expresses preference for a push button in the main hold-on coil and implies a distrust of other methods; but the control of important circuit breakers involves multi-contact relays and depends upon an auxiliary d.c. supply, which experience has proved to be reliable.

The use of 3 300 volts is a step in the right direction, and I consider that more bad engineering arises from the adoption of too low than from too high a voltage.

Referring to the use of short-break or micro-gap switches, has the author any experience of the failure of these on frequent operation?

Concerning the question of air-break contactor gear versus oil circuit-breakers, each has its field of application, one important point in favour of the air-break devices for frequent duty being the cost of oil renewal of the alternative design. For both types of gear, silver contacts give improved results.

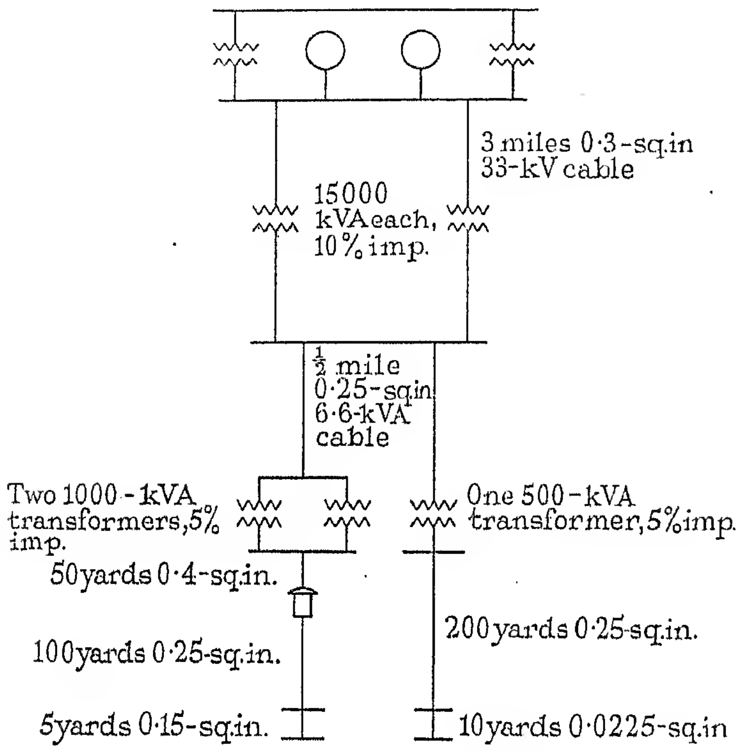
I am able to confirm the figures given in the paper for the rupturing capacity of interrupting devices on consumers' premises. The fault current on a typical 400-volt network varies from 40 000 to 7 000 amps., but is rarely less. The basis on which these figures have been obtained is shown in Fig. B.

Finally, it would be interesting to know whether the curves shown in Fig. 11 are based on experimental results or are due to theoretical calculations.

Mr. J. C. Jones (*communicated*): The paper deals mainly with control-gear design in relation to distribution switchgear; but the aim of the control-gear manufacturer is to protect the motor against any dangerous electrical condition which is likely to arise, and from this point of view the paper does not cover the whole subject. Short-circuit protection and earth leakage are only two of the considerations which must be borne in mind. I suggest that where motors are installed in a factory—as distinct from the central source of electricity supply—

short-circuit protection at any rate is best provided in the distribution fuse-boards, one of which should be allocated, in the case of, say, a machine shop, to each machine tool but not necessarily to each motor.

I should like to mention two points which deserve more consideration, on the part of either control-gear or motor makers, than they have had up to the present. First, there is a demand for a cheap and reliable method



	Percentage impedance on 10 000-kVA basis		Fault current (amperes)	
	Case 1	Case 2	Case 1	Case 2
Grid power station ..	1·0	1·0		
Primary voltage system .	0·69	0·69		
Main substation	3·33	3·33		
Secondary voltage system	2·5	2·5		
	7·52	7·52		
Network substations ..	25·0	100	44 000	13 500
Feeder pillar	22·2			
Distributor	74·0	148·0		
Service cable	5·6	71·5	10 700	4 400
	134·3	327·0		

Fig. B

Case 1. Low-voltage consumer, small factory in industrial area fed from substation with two 1 000-kVA transformers.
Case 2. Low-voltage consumer. Residence in suburban area fed from substation with one 500-kVA transformer.

of protecting the motor against running as a single-phase machine owing to an open-circuit in one of the lines or a failure in a fuse. Experience shows that this type of fault is not infrequent on small 3-phase motors where the stator windings and connecting cables are of small section, and in any case it is difficult to get close overload protection. Secondly, there is the question of excess-temperature or overload protection in the motor itself. In the application of motors to high-production machine tools it is not uncommon for the motor to be subjected to very heavy momentary overload up to a figure approaching the pull-out torque of the motor, and these heavy overload conditions occur with each part produced on the machine. The production of such a machine may easily be 100 parts per hour, and it is generally found in the case of thermal overloads that the standard size of heater has to be increased or, in the case of magnetic overloads, that the extent of the delay has to be lengthened. Under such conditions it is easy for the motor to overheat, and there is no doubt that the correct place in which to install overload protection is in the motor itself. There is a device of this kind on the market, but so far as I know it has not been applied to any great extent.

I am convinced that there are a very large number of motor drives in various industries where this condition arises, and in most designs of protected squirrel-cage induction motors it would be a comparatively simple matter to fix some excess-temperature trip device on the outside of the stator laminations but inside the yoke for interconnection with the no-volt trip of the starter. It would be interesting to have the author's opinion on these two further aspects of motor protection.

Mr. J. Solomon (*communicated*): The need is evident for more attention to the sectionalizing of modern low-voltage networks in order to avoid too great a concentration of fault current at one point. It should, however, be realized that quite moderate lengths of cable will reduce the short-circuit current to a figure within the breaking capacity of standard types of oil circuit-breakers. In a short-circuit testing plant the conditions are usually more severe than in the field, but more knowledge of the short-circuit currents actually experienced on factory and domestic premises is urgently required in order to help the industry to settle the limits of breaking-capacity requirements for low-voltage installations.

With regard to the performance of fuses, the present British Standard Specification (B.S.S. No. 88—1931) has been based mainly on experience with the semi-enclosed porcelain type of fuse. Subsequent knowledge of the performance of modern high-rupturing-capacity cartridge fuses has led to a great advance in the requirements for standardizing fuses, and the revised form of B.S.S. No. 88, which is at present under consideration, will recognize the experience gained within recent years. Current ratings will be standardized up to 800 amps., and the short-circuit ratings will be related to the duty of the fuse in interrupting the "prospective current" of the circuit to be protected.

The author suggests a fusing factor of 3 to 3·5 for short-circuit back-up protection of motor circuits. It would appear desirable to discriminate between direct-on starting and star/delta starting. From certain published data, it appears that one manufacturer has adopted a fusing factor of the order of 2·5 to 3 for direct-on starting and 1·5 to 2 for star/delta starting. In the light of the author's experience, are these figures satisfactory?

The physical characteristics of tinned copper fuse wire have been the limiting factors in fixing a fusing factor of the order of 2 for overcurrent protection with the semi-enclosed type of fuse. As it is now customary to use other materials than copper for cartridge fuses it is

possible to arrive at lower fusing factors for overcurrent protection. It would be interesting to have the author's views on this point.

Mr. C. A. M. Thornton (*communicated*): Surely when dealing with the rupturing capacity of l.t. circuit breakers (page 145) the capacity of these breakers for making circuit under short-circuit conditions ought not to be omitted, because it is becoming increasingly realized that the latter is the more arduous condition with l.t. circuit breakers.

With regard to flashovers to case with a.c. contactors (page 149), it is very dangerous to assume that an a.c. arc in air always takes place with the small amount of arcing indicated in the films shown by the author at the meeting. My experience indicates that a 400-volt a.c. arc in air may spread nearly as far and as easily as a 220-volt d.c. arc.

May I inquire the reason why more contact wear has taken place on oil-immersed switches than on air-break switches of equivalent design (page 150)? Can it be because contacts under oil must be cleaned up after arc rupture, because they cannot be observed, whereas contacts in air should receive and need a minimum of cleaning?

The high-rupturing-capacity fuse characteristic curves in Fig. 11, plotted with double logarithmic scale and scaled in powers of 10 for amps., minutes, and seconds, surely represent perfection. Is it too much to hope that all manufacturers who publish characteristic curves of their fuses will soon standardize on this form of graph? It would also be valuable if information could be given as to how the current values for very short times (say, below 0·1 sec.) are estimated, because they obviously cannot be produced in practice.

In Table 3 it surely is of little value to list circuit breakers of 50 to 75 000 kVA rupturing capacity at 400 volts, because breakers of such a great "making" capacity at 400 volts are not practical propositions. In this connection it is interesting to note (page 154) that a 400-volt breaker has a 10 per cent internal voltage-drop under short-circuit conditions.

Tables are provided in the *Cable Research Handbooks* (vol. 2) of the impedance of various cables at 50 cycles per sec. and under normal conditions. It appears that these values are generally used when short-circuit currents are calculated. It would, however, be interesting to know how the values so obtained compare with test results. Owing to the prominence of harmonics under short-circuit conditions one might reasonably expect wide differences.

There must be a real need at the present time of authoritative information sufficiently accurate to enable engineers to estimate whether their low-voltage circuit breakers are capable of doing their job and at the same time not erring out of all reason on the side of safety.

[The author's reply to this discussion will be found on page 173.]

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 16TH FEBRUARY, 1937

Mr. F. Johnston: Does the author know of any method by which insulation tests can be carried out between conductors periodically, without taking the system out of commission? Such equipment would be very useful on board a ship where there are approximately 5 000 lights and a large number of motors. I should like to know of any system by which an electrician on board could keep a record of lowering insulation values which must occur as the ship gets older. At present there is no practical method of making such tests without disconnecting the lamps, motors, etc., and laboriously testing section by section.

Mr. Joseph McCandless: It is surprising that no mention is made in the paper of the desirability of providing sensitive earth-leakage protection on heavy-current circuits. Apparently the author is content with overload protection on all phases. If a large motor circuit is protected by, say, 200-ampere fuses on a 400-volt 3-phase system, the voltage to earth being 230 volts, operation of the fuses will not occur if the total resistance in the earth circuit is more than $\frac{1}{2}$ ohm. This resistance includes the resistance of the earths both at the substation and at the motor installation. It appears to me, therefore, that under the conditions I have stated there is no protection against earth faults and that these will persist until a phase-to-phase fault develops. The fuses or circuit breakers then have to operate under very severe conditions, whereas, had earth-leakage protection been installed, the fault would have been cleared while a very limited fault current was flowing. Apart from this aspect, the damage done to motor windings and equipment is much more extensive than would have been the case had earth-leakage protection been fitted. I should like to know the author's views on this point.

I gather from the paper that the author would be content to fit a high-rupturing-capacity circuit breaker on a main distribution board and have a small motor starter on the system. Whilst this will ensure ultimate disconnection of the faulty circuit from the supply system it does not ensure the safety of the small motor starter, and I feel that in many cases if a heavy phase-to-phase fault occurred the starter contacts would have disintegrated before the main circuit-breaker operated. As this starter would usually be close to plant in a factory, there would be danger of operatives being injured. I am of opinion that if a motor starter is not capable of performing its job it should not be installed.

[The author's reply to this discussion will be found on page 173.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 22ND FEBRUARY, 1937

Mr. W. N. Waggott: The author refers to the protection of motors by thermal overload devices; such thermal devices as I have had experience of have proved practically useless, at any rate for the protection of essential power-station auxiliaries. The characteristics of the type of thermal device usually supplied with motor control gear bear no relationship to the heating characteristics of the motor with which the device is associated. If motor control gear is to incorporate protective devices these should be better than the type at present available. They should have a performance matching that of the motor.

The author suggests that the increasing use of contactors in motor circuits is due to the increasing demand for remote operation and for frequent opening and closing of the motor circuit. I presume he is referring here to air-break contactors. In the same paragraph he refers to economy in contactor design; prices of air-break contactors which have been laid before me in connection with recent work are rather high, and suggest that the air-break contactor if fully designed to do its job can be a very expensive item.

Dealing with the rupturing capacity of starters, the author states that high short-circuit values can be almost always avoided on low-voltage networks if there is a will to do so and if the basic idea of the layout includes this intention. Experience shows that it is difficult to arrange circuit conditions so that for low-voltage work the fault kVA is less than about 15 000. It requires a very good switch or contactor to stand up to a fault of these dimensions for the short time necessary for a back-up switch or other protective device to clear the circuit.

The author refers to the burning of contacts by operators not having the weight or knack to close heavy-current hand-operated 3-phase oil switches without drawing back after the first touching of the contacts. One point I have always stressed in connection with motor control-gear design is that the equipment must be of the quick-make pattern.

There is much yet to be done in connection with motor control-gear design, and progress will be in the direction of simplifying the gear. Thermal protection has had a fair trial, and I think it has led to complication in design and higher costs without achieving any material advance. Motor control gear for essential power-station auxiliaries should be of straightforward quick-make quick-break design, without any protective devices. The motor of to-day is a very reliable piece of apparatus and motor failures are very few. Where failures do occur it is generally found that they are due to mechanical reasons such as bearing troubles or to the motors installed being unsuitable for their duty. I would, however, recommend the installation of short-circuit protection at some point in the supply circuit to the motor control gear or at the point of supply to a group of motor control equipments, so that in the unlikely event of a fault occurring the shutdown would be of restricted dimensions.

Mr. S. C. Lloyd: It is suggested that all starters should be fitted with interlocked isolators to ensure full compliance with the Home Office Regulations. I do not agree with this, as my understanding of these Regulations is that some provision must be made for cutting off the supply to the various motor control circuits, and 75 per cent of the starters sold to-day are not fitted with the isolator as part and parcel of the switch unit.

With regard to boiler-house gear, to obtain a satisfactory boiler-house layout of control and distribution gear it is desirable that all control and distribution gear should be left out of the boiler-house specification and treated as a separate specification. By this means it is possible to avoid various types of starting gear being supplied through different fan makers, stoker makers, and pump makers.

Blow-outs should always be fitted to contactors for use on direct current, and on alternating current where there are no blow-outs the contact life is, of course, considerably reduced. For heavy service I would suggest that blow-outs be fitted on contactors above the 25-amp. size.

With regard to short-break switches, the idea of breaking 100 amps. with a 0·01-in. break is very interesting. I do not know of any 100-amp. starters with so small a break, but if this is satisfactory present-day designs of starters are too large.

With regard to arcing to cases, there should not be any trouble in this respect, provided the cases are designed so as to be suitable for the duty which the contactor is called upon to do.

On page 151 mention is made of short-circuit values of 25 000 kVA. Standard commercial starters are not suitable for such duty, and where this requirement has to be met it is essential to use also high-rupturing-capacity fuses.

Mr. Waggott mentioned the high cost of contactor gear, and the fact that it is too complicated. Manufacturers have to quote to the requirements of their clients, and this of course determines the price question and the nature of the gear offered.

In regard to thermal overload trips versus magnetic overload trips, could the author give the advantages of the two, and also his recommendation as to the maximum current on which thermal trips should be used? Also, has he any recommendation regarding the use of oil dashpots at temperatures of, say, 120° F.?

Further, has he had any experience of testing for high rupturing capacity with a d.c. battery?

Heavy service produces corrosive gases, and where the gear is enclosed special care is necessary in the design of arc chutes to take care of this feature.

As to the relative merits of oil-immersed and air-break switches, my experience is that there is less maintenance with the latter, especially where the service is very heavy.

Mr. J. Gibbins: The use of a high distribution voltage is undesirable from the user's point of view because it means installing both 400-volt and 3 000-volt switches and transformers in the substation. The one cannot be a standby for the other, and the price per kVA increases for switchgear, transformers, and condensers, as the size decreases. In the smaller sizes the light-load losses are increased whilst the average power factor decreases.

On page 148, 100 000 to 150 000 kVA is given as the economic limit of breaking capacity at 3 000 volts. What is the economic breaking capacity for the 1 500-amp. 400-volt circuit breaker, which is given as the economic low-voltage size?

Concerning contactors (page 148), it would be helpful to know how the price of contactor plus high-capacity fuses compares with that of a hand-operated oil circuit-breaker.

On page 151 the author refers to the increasing use of power in main distribution circuits. From old catalogues one can find, however, that 3 000- and 5 000-amp. circuit breakers were made 30 years ago.

Mention is also made in the paper of loads of 250 000-kVA on the e.h.t. side and 20 000 kVA on the l.t. side. In this case the impedance of the transformer is 12 per cent; it is clearly very difficult for the supply undertaking to maintain a constant voltage over the system when the impedance of transformers may vary from 3 to 12 per cent.

Referring to Fig. 12 (Plate 2), do the first three views show the bouncing on making?

Finally, I should be glad to know how the author's insulation indicator works.

Mr. G. J. S. Drury: I should be glad if the author would give further information regarding the ionization mentioned under the heading "Operating Experience" on page 149.

In machine mining it is becoming the standard practice to control coal-cutters and conveyor motors by contactor starters enclosed in explosion-proof cases. These starters are normally called "gate-end boxes." Trouble was recently experienced on one installation where ionization was apparently taking place, and the result was that an acid was formed in the enclosure which affected some of the moving parts. It is, of course, impossible to make a piece of apparatus absolutely air-tight, even though all joints have machined surfaces. Apparatus must "breathe," and "breathing" draws in the pit atmosphere. Under some circumstances water may find its way into the apparatus, and the water found in some pits contains a slight amount of sulphur. It would appear as though cooling the arc more would help matters. Will the author kindly give his comments on these points?

Mr. C. S. Lawson: I agree with the author's statement that although short-circuit testing of fuses with a d.c. battery supply gives more consistent results than with an a.c. supply, the d.c. test may not be a correct

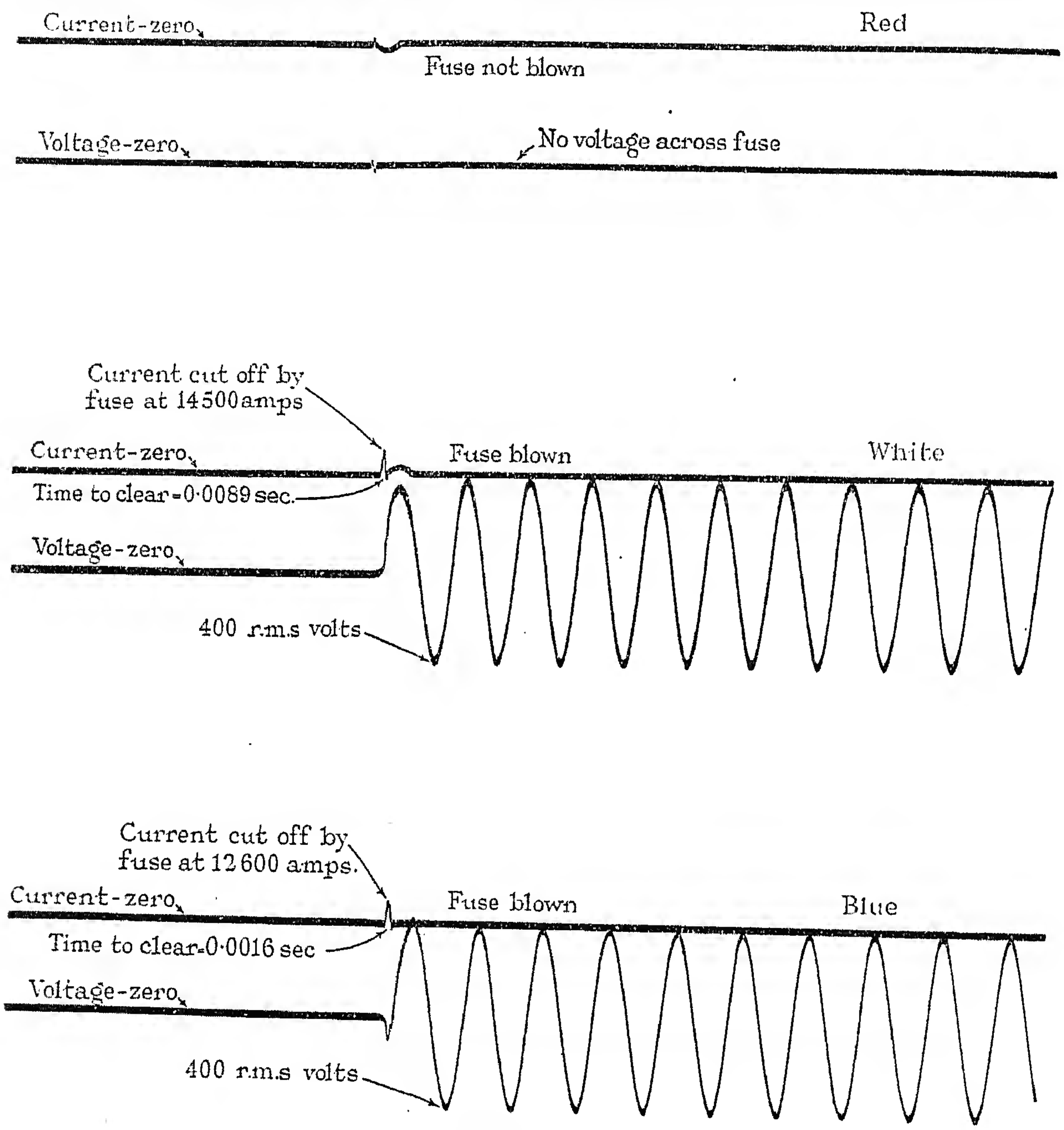


Fig. C

guide to the performance of a fuse on alternating current, since under the latter conditions the fuse may be called upon to deal with peak values of current and voltage. I cannot, however, agree that a 3-phase test is necessarily representative of 3-phase service conditions, and I will try to explain this further.

As the author points out, the condition often arises in 3-phase operation of fuses that two of the three fuses have to clear at full line voltage, and 3-phase testing by no means necessarily reproduces this maximum-severity condition. Furthermore, 3-phase tests show great inconsistency in respect of voltage severity. In Figs. C and D, oscillograms are shown of typical 3-phase short-circuit tests on identical 200-ampere fuses in exactly the same circuit with a prospective current of 37 000 symmetrical r.m.s. amperes at a test voltage of 400 volts, 3-phase.

Fig. C indicates that the test was severe, since two of the fuses had each to withstand full line voltage of 400 volts. The reason for this was that the fuses in the white and blue phases melted first and, as can be seen from the oscillogram, their current paths were of such resistance that the current in the circuit was cut down with extraordinary rapidity. Thus the current through the fuse in the red phase was not permitted to reach a value sufficient to blow this fuse, which consequently did not melt, but became practically a link in its phase. Each of the other two fuses was therefore in effect being tested as a single-phase fuse at full line voltage. This is a condition which can arise if the network of the supply is unearthed or if the fault is a phase-to-phase fault.

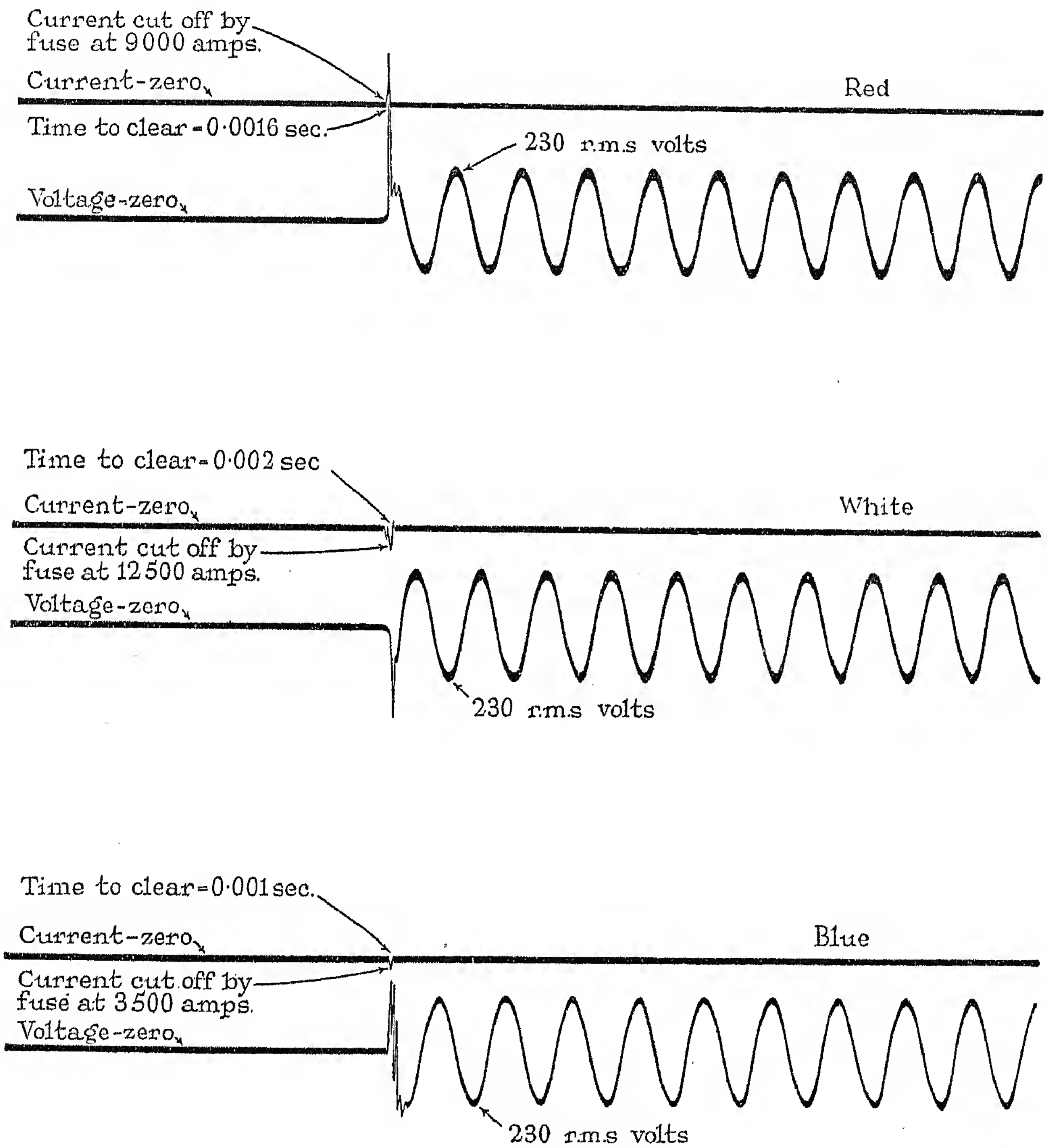


Fig. D

Fig. D is an oscillogram of a test on a circuit identical in all respects, but it illustrates the other extreme in the range of severity, namely the easiest. In this test the three fuses all melted and the voltage at each of them was of the order of 230 volts (the phase-to-neutral voltage), which is an easier condition than the 400 volts of the other test. The two tests thus represent the extremes of voltage severity obtainable in the ordinary course of 3-phase testing of fuses, and practically any intermediate voltage severity may also be obtained. On the other hand, single-phase tests on single fuses at ful

line voltage always reproduce the essential worst severity conditions of 3-phase operation.

I am pleased to see that the author mentions the advantage to be gained from the current cut-off effect of fuses under short-circuit conditions. This feature, which is very pronounced on short-circuit, relieves the protected apparatus of electromagnetic stresses and heating effects which would occur if the short-circuit current was permitted to rise to its maximum value. This current cut-off effect, however, is less the greater the current rating of the fuse, and therefore in order to obtain the maximum benefit from it the current ratings of fuses should be kept as small as possible.

I noticed that during the demonstration which the author gave of the operation of a contactor in series with cartridge fuses the blowing of the fuses was accompanied by a fairly heavy puff of smoke, which seemed to come from the indicators fitted to the fuses. This emission would be likely to cause a flashover either between phases or to a metal case, and I consider that an indicator should operate without any external smoke or flame. It must be remembered that, in addition to providing indication of the blowing of a fuse, an indicator of the type used must be capable of clearing satisfactorily the full circuit kVA under short-circuit conditions. This latter function is really more important than indication, and unless due consideration is given to it in design the full severity of a short-circuit may be transferred from the main fuse to the indicator fuse, with dangerous results.

The more scientific development of the cartridge fuse is now removing the adverse impression created by the uncertainties of its predecessor, the open-wire fuse, and for this reason I welcome the author's references to some of the advantages to be gained from the use of fuses.

Mr. E. H. B. Martin: The use of contactor gear enables a machine operator to devote his full attention to the machine and to perform even complicated electrical switching operations almost subconsciously, by pressing a button. Further, it is safe to permit unskilled or semi-skilled labour to control electric motors by means of contactors, since the main switching operation will always be carried out correctly and under ideal conditions, even if the operator is hesitant and slow in operating the master switch or push button. Should there be a fault on the line a contactor is capable of making on to a higher-capacity fault than it will break, and since it is the function of the fuse or circuit breaker in the main circuit to clear faults the contactor is the most safe and efficient form of motor control gear.

The paper refers at length to the thermal relay, which is playing an increasingly important part in motor control gear. This form of relay was first developed in the U.S.A., where it has now practically supplanted all other forms of protection. It has also become probably the most widely used type of protection in this country and on the Continent. Although, owing to the difference in heat capacity, the thermal relay does not exactly follow the heating curve of the average motor, it is by far the most accurate type of protection against overheating of the motor that has yet been devised, and records show that it does not give more trouble than most other items of control gear. The comparatively long inherent time-lag at high overloads tends to delay the operation of the associated control gear under fault conditions, until the back-up protection has operated.

Mr. R. W. Mann: I am not sure what message the author means to convey: Has he mainly in mind a word of warning to the user, or is he asking for a greater measure of co-operation between designers of equipment? While it is true that a considerable amount of research work has to be done on the subject of starter breaking-capacities, it must not be forgotten that such work is being carried out continuously by motor, switchgear, and control engineers in practically all large factories manufacturing complete equipments.

As regards the author's preamble on the difficulties of the purchaser, a happy solution of the problem would appear to be the making of one electrical firm the main contractor for all electrical equipment and cabling, so that, apart from layout, some measure of standardization could be effected.

The author suggests that the users' problems can be simplified if not solved by the employment of a qualified electrical engineer by the machine-tool makers. Such a solution would be uneconomic from the tool-makers' point of view and largely unacceptable to the customer. It seems to me that the difficulty must be covered by a consulting engineer for large installations and by the electrical manufacturer for smaller installations.

The use of 3 000-volt motor layouts has become quite general practice, and while my own experience is limited to mining equipment and associated by-products I would imagine that the economical limit given by the author of 1 500 amps. at 440 volts is much too high a figure. I would subdivide my 400-volt network into sections carrying at least one-third of this current.

I fail to understand the author's illustration of his point in Fig. 4; the introduction of duplicate feeders would appear to be beside the point, and if a comparison of cost is to be effected it would appear to lie between layouts (*a*) and (*c*). The reason for adopting 1 000-kVA transformers in (*c*) needs explanation.

I would suggest that one of the reasons for the increasing application of contactor gear lies in the advantage of foolproof operation by casual or unskilled labour. The three suggested difficulties in the design of contactors are all applicable in equal measure to hand-operated starters and are all a question of effective design.

The author's main problem deals with the rupturing capacity of small starters, and an easy solution of this problem does not present itself. It is certain that, with the increase in the power behind the supply mains, if the purchaser is faced with the purchase of high-rupturing-capacity starters for even the smallest motors then the use of electricity must receive a heavy setback. There must be thousands of switches and starters in this area which, owing to the increase in output capacity of the power supply mains, are quite incapable of dealing with a 3-phase short-circuit. There would appear to be three alternatives: (1) To ignore the problem. (This probably represents the attitude of 95 per cent of the purchasers of small starters and switches to-day.) (2) To subdivide the system into transformer-controlled units

arranged to bring switchgear and starters somewhere near their rupturing capacity, and to accept the chance of a 3-phase short-circuit destroying the starter internally without serious chance of external damage. (This, for the moment, represents my policy.) (3) To design starters with adequate breaking capacity (a commercial impossibility) or to combine with the starter a high-rupturing-capacity fuse. The author discusses alternative (3) at some length and, on paper at least, he proves his point; but there would appear to be too big a tendency to limit his experimental data to severe short-circuits. I am not yet convinced that somewhere between normal overload (to be dealt with by the starter's overload protection) and severe short-circuit (to be dealt with by the fuses) there is not a point where the short-circuit is of such a magnitude that the starter contacts will commence to move before the fuses disrupt the circuit—with possible collapse or welding-together of the contacts.

[The author's reply to this discussion will be found below on this page.]

WESTERN CENTRE, AT SWINDON, 22ND MARCH, 1937

Mr. W. Roberts: The author makes a good point of the fact that, provided the arc is controlled during the process, an a.c. arc will extinguish itself at the first or second half-cycle, and that all that is wanted is to prevent it restriking. What are his views in regard to copper dampers or similar devices for splitting up the arc?

In the author's opinion is a blow-out effective on alternating current? Some makers use these but they are of the very light type, more for the purpose of directional control of the arc than for use as blow-outs.

One of the author's films showed a much more vicious arc coming from the top of the arc box where this is close to the contacts than on a similar contactor which has no arc box. I presume that the size of the arc box is a compromise in that it allows ample space around the contacts to dissipate the arc gases, but at the same time is not so large that it ceases to have some cooling effect.

Experiments have been made with a view to interlocking a contactor with an ordinary drum controller, but one of the troubles is that a fast operator can always race the contactor, and go from first forward to first reverse before the contactor has opened. Is it practicable to speed up the operation of a contactor to avoid this, at least on direct current?

Mr. W. A. H. Parker: I was very interested in the author's remarks regarding the use of 3 300 volts for motors above 100 h.p. in order to reduce the large currents dealt with by the switchgear at starting, and I believe that, taking everything into account, the total capital cost and maintenance of the higher-voltage equipment would be less if this practice were adopted.

With regard to the use of high-rupturing-capacity fuses, there is a definite field for this type of apparatus where there is any doubt about the capacity of existing switchgear to clear increased short-circuit conditions. In a particular case that I am interested in, current transformers of 10/5-ampere ratio have to be used on a 6·6-kV metering equipment and may have to deal with 75 000 kVA under fault conditions. In addition to the thermal limits of the current-transformer windings, the designers have to take into consideration the magnetic limits, and it may be necessary to insert fuses in the circuit to provide the necessary safety-valve.

Mr. T. Hood: At the Manchester discussion on this paper I was much impressed by the remarks I heard regarding the great necessity, in some industries, of maintaining continuity of supply; whatever protective features are introduced on the circuit breakers through which supplies are afforded, they must be such that only when external conditions of peril arise should these master protective features operate.

I should like to refer to the author's point concerning the reactive effect of using rectangular-strip copper busbars. I understand that if such busbars are made in channel or other form this "choke" effect can be substantially reduced.

Circuit breakers of large capacity are now being made, by some of the larger German manufacturers, to operate safely in air. Has the author any knowledge of a medium other than oil being used to ensure arc rupture on breakers employed on low- or high-voltage circuits?

Mr. J. R. W. Grainge: The increasing short-circuit capacity of generating and distributing plant has added to our difficulties. Circuit breakers installed a few years ago can no longer be regarded as adequate owing to this increase, and it is to be hoped that in addition to the many improvements already made designers will produce a circuit breaker capable of doing its work in such a way that its capacity for protection is not impaired by these outside changes.

The difficulties do not end at the circuit breaker. A cable large enough to do its work comfortably and with a reasonable margin will fail if its temperature limit is reached before the circuit breaker has had time to do its work. There is, therefore, the money that will be spent on current-limiting devices available for improving the circuit breaker, and there is the added advantage that the absence of this device means one less piece of apparatus to maintain.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, LIVERPOOL, MANCHESTER, BELFAST, NEWCASTLE, AND SWINDON

Mr. J. O. Knowles (*in reply*): First, with regard to the scope of the paper, those who in the various discussions agreed with my points, nevertheless in the main agreed that they were worth making.

Mr. Mann asks quite rightly what message I meant to convey. In a general paper, however, on subjects which have not been closely argued in I.E.E. papers, it has been more in my mind to ventilate subjects which I have found engineers in various parts of the country very ready to discuss, rather than to plead a particular cause. In

each section I have been at pains to represent views held in common by at least several manufacturers. The general thread of the argument throughout is run on the borderline between motor control gear and distribution switchgear, connecting these two types of gear rather than describing either.

In my detailed reply, which follows, the various sections of the paper are separated into headings roughly corresponding to the headings in the paper itself.

Grouping and Isolating of Motor Switchgear

Mr. Waygood and others stress the fitting of interlocked isolators to starters, a view more akin to my own than that of Mr. Lloyd whose argument (that they are not fitted to the majority of starters today) is, however, true in regard to the large number of simple starters of small horse-power fed from fuseboards in view of the driven machines. I should be happier if the ways of these fuseboards were more often labelled with the circuits controlled.

Mr. Evans is also concerned with safety and Home Office regulations and does not wholly agree with Mr. Mellonie, whose trust in multi-contact relays and an auxiliary d.c. supply refers perhaps more to operating conditions rather than isolation. My view lies between that of Mr. Mellonie and that of the L.C.C. regulations, which trust nothing but a motor isolation switch placed practically at the motor itself. (In the special case of latched-in contactors—mentioned by Mr. Evans—having d.c. shunt trips, I prefer the starter isolating switch to open the latch mechanically.)

Co-operation between the engineers of the various firms who combine to build up a complete plant is stressed by Mr. Waygood. Mr. Lloyd and Mr. Gillespie deplore the inconsistent choice of control gear made by various contractors in the same installation, and ask in effect for one make instead of a "mixed lot." Mr. Mann goes further and suggests one electrical firm for all the electrical work, though Mr. Lloyd more nearly relates his remarks to my particular point and is very drastic in asking for the motor control gear and the distribution gear to be in one specification, which apparently he is content to see separated from that containing the motors.

Mr. Mann does not agree with my plea for an electrical engineer on the staff of machine makers, but slightly confuses the issue by referring to installations. I was referring to the designing of an individual machine tool. To obtain the best results, the mechanical and electrical designers of the machine should work in daily touch with each other. Regarding the economics of the matter, it is at least true that the machine-tool firms who have appointed electrical (designing) engineers have reaped a considerable benefit and have been in the forefront of the advances made in the standardization of electrical control of machine tools. Moreover, collaboration between electrical firms and "mechanical" firms has been found more difficult where the staff of the "mechanical" firm does not include an engineer really familiar with advanced practice in motors and control gear.

With reference to the grouping of starters on busbar chambers, the use of this construction is dependent to some extent on the grouping of the motors. Mr. Waygood finds that this grouping can be justified even in cases where extra capital cost is incurred. I would emphasize that, in many instances investigated, the grouping of starters has not even meant additional capital cost, but there is usually only a saving where a number of large motors are installed in a group. Dr. Wilson points out a particular type of arrangement where a saving has been effected—the use of one starter for several motors. It was, however, only my intention to suggest a line of thought which can be worked out and judged on its merits in particular instances.

In reply to a comment on detail by Mr. Gillespie, grouped control panels of the types illustrated in the paper have easily removable back doors, except in the case of wall-mounting units, where the whole panel can be easily removed from the front.

Regarding the particular case of grouped starters for boiler house auxiliaries, I agree with Mr. Coldwell that the starters for induced-draught fans on the roof and forced-draught fans in the basement cannot be grouped, though the push-buttons and ammeters can be mounted together. The basic idea is to group for convenience, and this idea works out in different forms in different installations. Both Mr. Coldwell and Mr. Evans accept the principle of alternative supply (though Mr. Coldwell prefers the tee system to the ring main), and thereby answer Mr. Mann, who considers duplicate feeders irrelevant (not unnecessary). Mr. Mann weighs up the cost of the various arrangements in Figs. 4(*a*), 4(*b*), and 4(*c*), but I introduced Fig. 4(*b*) to stress the problems associated with the provision of alternative supplies on the l.t. side. Cost is a secondary consideration to continuity of supply, especially in boiler-house installations where the whole cost of starters and l.t. distribution gear for the boiler auxiliaries may not be more than 1 % of the cost of the whole installation.

While the boiler-house installation is only a particular case of the problems associated with the layout of distribution gear and motor control gear, I consider that it is a striking instance of the variety of opinion on this matter. In my experience of many installations, hardly two have the same electrical layout for the supply to the auxiliary motors. A separate paper would be required to do justice to this subject.

Use of 3 300 Volts in Motor Circuit

Referring to Fig. 5, Mr. Evans refers to the conductors on the line side of the fuses as being the most vulnerable part of the arrangement shown. It is, however, much less difficult to make these conductors safe against electromagnetic stresses and the heating effects of heavy fault through-currents than those of low voltage. In a recent test a short-circuit of 20 000 kVA at 380 volts (3-phase) applied for a total period of 5 seconds (two tests each maintaining this fault for $2\frac{1}{2}$ seconds) bent a connection $1\frac{1}{2}$ in. × $\frac{1}{4}$ in., supported at ends 3 ft. apart, $1\frac{1}{2}$ inches in the middle towards an earthed frame which was 3 in. from the conductor at the commencement of the test. The same fault current would require 175 000 kVA at 3 300 volts, and 5 seconds is a long time for a short-circuit to be maintained!

Mr. Evans rightly queries the full-load currents given in the advance copies of the paper for 300 h.p. motors on 400 and 3 300 volts. The obvious errors have been

corrected for the *Journal*. He also mentions that the starting current of 100 amperes for a 200-h.p., 3 300-volt motor involves a high-reactance rotor. The case taken was certainly that of a special design having a particularly low starting current, but this case was selected partly to show that the high stator voltage does not restrict the design of the motor.*

If the same rotor design had been used with a stator wound for 400 instead of 3 300 volts, the starting current would have been over 800 instead of 100 amps., and the main point of my argument in this instance was that a starting current of 100 amps. at 3 300 volts damages contacts much less than a starting current of 800 amps. at 400 volts. When reading the paper I showed a slide of two contacts which illustrates this point very well and which is now reproduced as Fig. E (see Plate 3, facing page 176).

There are obviously different views regarding the use of 3 300-volt motors. Mr. Clothier agrees that " the use of 3 300 volts is desirable for the larger motors." Mr. Mann says " the use of 3 000-volt motor layouts has become quite general practice " (in mining equipment). Mr. Mellonie considers that the use of 3 300 volts is " a step in the right direction," and Mr. Kidd agrees with him that " a more extensive use of higher-voltage motors will be made in the future." Mr. Reynolds says " As long as 25 years ago, we were installing high-voltage motors for the heavy drives in rolling mills and factories," and adds that " these motors have involved less trouble and less expense of maintenance than low-voltage motors of the same size." Mr. Parker believes that the *total* cost of installation and maintenance might be reduced by using 3 300 volts for large motors, and other speakers reinforce this opinion by considerations of the rupturing capacity of l.t. circuit breakers (q.v.).

Mr. Allcock agrees that the use of 3 300 volts on certain installations is possible, but gives two instances where it was considered impossible, and I agree with him in this. I do not, however, agree with his solution in his first instance, without further knowledge of the circumstances. Several engineers who have accepted as inevitable a layout requiring 4 000-amp. 400-volt circuit breakers and a main 400-volt switchboard of 40 000 kVA rupturing capacity have shown these switchboards to me with the comment that they would think, not twice, but a third time before they accepted this layout as inevitable again. Mr. Allcock himself criticizes the layout as " undesirable," and in the words of Mr. Mellonie " more bad engineering arises from the adoption of too low than from too high a voltage," though I could not apply this comment to past installations without condemning some of my own efforts!

A suggestion worth noting is indicated in Mr. Allcock's first example—the use of interlocked incoming breakers, presumably interlocked so that the main and standby transformers cannot be paralleled. This arrangement is discussed later in this reply under the heading " Short-circuit ratings of circuit breakers," but has obvious disadvantages where a change-over from one transformer to the other should be made without interrupting supply. I am content at this stage to record that the concentration of large blocks of power on one l.t. board is being increasingly criticized, and to take up a position between that of Mr. Gibbins—who points out that 3 000-amp. and 5 000-amp. circuit breakers were listed 30 years ago—and that of Mr. Mann—who considers that the economical limit of 1 500 amps. at 440 volts which I gave is much too high a figure. I at least agree with Mr. Mann in his basic idea of subdividing the l.t. network, though if this idea is pursued to the degree suggested by Mr. Mann the argument of expense put forward by Mr. Gibbins will apply with more force. Another point worth noting in this connection is that the switchgear associated with transformers may tend to become simplified. This tendency is apparent in some e.h.t. layouts outside the scope of the paper, but is also indicated in Mr. Allcock's second example, where he speaks of using an isolating switch instead of a breaker on the l.t. side of the main transformer, relying on the breaker on the h.t. side to clear a busbar fault on the l.t. board. I would, however, in the instance given, introduce current transformers on the l.t. side operating overload and *earth-leakage* relays, these relays tripping the h.t. breaker. It is obvious that earth-leakage relays are particularly desirable on l.t. heavy-current circuits.

As to the size of motor which can be wound for high voltage, questions of motor design are outside the scope of the paper, but Mr. Reynolds and Mr. Kidd point out that the common h.t. distribution voltages are 6 600 and 11 000 volts and that the use of 3 300-volt motors means transformation from these voltages. Mr. Highfield gives a note of warning to those who speak of motors of comparatively low full-load current when wound for 6 600 or 11 000 volts—the constructional difficulties associated with small-section armature conductors bearing heavy insulation. Another difficulty more relevant to the paper is that conductors of small section in the motor, the cables, and the current transformers, may not withstand high short-circuit currents for a sufficient period.

Contactors

Mr. Evans considers the micro-gap switch irrelevant, but Mr. Lloyd and others find it interesting. Since this paper was written, the micro-gap switch has been the subject of a paper* read before The Institution by Prof. W. M. Thornton. Its relevance to contactor design is two-fold—first, to emphasize the difference between breaking d.c. and a.c. circuits of the same current and voltage (see also Figs. F and G, Plate 3), and secondly, because the butt contacts of a contactor open only a short distance during the first half-cycle of arcing. In any switch with sliding contacts (such as an oil switch with wedge contacts or a knife-switch) the moving contacts have acquired a velocity before they separate from the fixed contacts, but in a contactor or any butt-contact switch the moving contact rests on the fixed contact (even though it may roll slightly) up to the instant when contact separation begins, and although the whole of the opening movement may take several half-cycles the separation in the first half-cycle is small. The actual distance moved in the first half-cycle varies with the size

* An exception to this statement is, however, the special case of 2-speed motors having two stator windings. The difficulty of insulating the windings from each other increases with the supply voltage and has much restricted the use of 3 300 volts for boiler-house installations, where the large fan motors are frequently of the 2-speed type.

* *Journal I.E.E.*, 1937, vol. 80, p. 457.

and design of the contactor, but it is an important point in a.c. contactor design and approximates to Mr. Reynolds's suggestion of a switch which has a short break over a period of one half-cycle (why 2 or 3 cycles?) and a subsequent longer break for isolation. Mr. Roberts suggests that the opening of the contactor might be slowed up. A marked shortening of arc length was effected in a butt-contact air-break change-over switch by link mechanism designed to slow down the early portion of the butt contact travel compared with the movement of the operating handle, but although similar link mechanism can be applied to a contactor there are simpler ways of sufficiently controlling the acceleration of the butt contacts from rest.

Several speakers stress the suitability of contactor gear for unskilled operation. I am more concerned (within the scope of the paper) to stress the suitability of contactors for *frequent* operation. Mr. Kidd's remarks are interesting on this point. He says after investigation and trial that "when frequent operation is necessary, contactor gear is the only reasonable proposition," and is supported (within reasonable limits) by Mr. Mellonie, Mr. Gillespie, and Mr. Lloyd.

Mr. Gillespie does not think that contactors are less robust than circuit breakers (why should he think that I do?). The "numerous coils and relays" mentioned by Mr. Kidd are not necessary where the contactor is only fulfilling the same function as a hand-operated starter, and Mr. Lloyd reports less maintenance with air-break than with oil-immersed switches, especially on frequent, heavy service—a point mentioned in the paper with particular reference to contact wear.

With regard to oil renewal, and in reply to Mr. Evans, oil sludging *is* a factor but not the only factor in contact wear on oil-immersed switches. Mr. Thornton states that contacts under oil must be cleaned up after arc rupture, and Mr. Mellonie speaks of the cost of oil renewal. I have seen the oil in a distribution circuit-breaker looking like new oil after a year's service on a switch which probably never had to operate under load, and I have also seen oil which, after a week's service, was hardly recognizable as switch oil. Whereas oil-immersed switches are apt to suffer from too little maintenance, contactors are apt to suffer from too much—particularly too much filing of contacts.

Mr. Scarf asks whether the contact burning which takes place under oil can be reduced by suitable contactor design. It can, but my knowledge is frankly not sufficient to give general laws independent of particular designs. Even in air the design of the arc chute can make a considerable difference, as Mr. Scarf himself points out in giving information on the special problem of the formation of corrosive gases in explosion-proof cases mentioned by Mr. Drury.

Mr. Roberts notes in regard to the size of the arc box that a compromise may have to be made between cooling surface and venting space. Copper dampers and similar devices may also be of assistance in restricted spaces.

Mr. Roberts also asks whether blow-outs are effective on alternating current. This question, like the question "Are pictures beautiful?" can be answered by saying "Some are, for some situations," and I would prefer to comment on particular designs. In general, however, I have found that a.c. contactors without blow-outs can be designed for at least 300 amps. without presenting any difficulties in service on very varied forms of industrial motor control (see Fig. H, Plate 4).

Mr. Scarf mentions that the operation of a particular contactor was improved by the fitting of blow-outs. As he says the contactor was otherwise unaltered, it may be that the air-gap, speed of break, arc chute arrangement, and other factors, were more suited to a contactor designed to have a blow-out than to one designed to work without blow-out. It is a common belief that blow-outs on a.c. contactors are at least necessary "for safety" if the contactor should open on a current exceeding normal overloads, but I have recently broken 15 000 kVA and then 20 000 kVA at 380 volts, 50 cycles, 3-phase, on a standard contactor *not* fitted with blow-outs and enclosed in an earthed case under test-plant conditions at a very low power factor (0·15). The contactor was still in good operating condition without even a change of contacts and capable of carrying its rated load (380 amps.) after the tests (see Fig. J, Plate 4). Nevertheless, I recognize that blow-outs have their place in a.c. contactor design, but not to the extent that some people maintain.

Questions of cost (raised by Mr. Waggott and Mr. Gibbins) depend, as Mr. Lloyd points out, on customers' requirements. In answer to Mr. Gibbins, a hand-operated circuit breaker is in general slightly cheaper than contactor plus high-capacity fuses. Where heavy short-circuits are possible, however, the cost will even depend on the time the back-up protection would allow the short-circuit to persist.

With regard to arcing to case, Mr. Lloyd points out that there *should* not be any trouble in this respect if, as Mr. Mann says, there is "effective" design. Mr. Clothier, on the other hand, considers that there is frequent call on the back-up fuse protection and points out where the trouble is most likely to occur—in built-in starters where space is at a premium. There is an increasing number of requests from machine-tool designers for reduction in the space occupied by contactor gear (even apart from any question of cost), and even for several contactors in the space considered a few years ago not too generous for one. While the successive requests for further economy in space have been successfully met by progressive development work, I considered it worth while to stress the danger of asking for or accepting a reduction in clearance to case, or other factors mentioned in the paper, which might give trouble on frequent operation. As Mr. Thornton and Mr. Evans both point out, an a.c. arc varies greatly with circuit conditions.

The short slow-motion loop films with which the reading of the paper was illustrated cannot be fully represented in the paper as printed. They supplement but do not replace oscillograph records, though "to see" does help one "to understand." In answer to Mr. Gibbins and referring to Fig. 12 (Plate 2), the pictures show successive stages in making and breaking circuit on a contactor having a considerable rolling action, and the first two pictures show (1) bounce at both initial and fully closed positions, and (2) bounce at fully-closed position. The shadow behind the contacts in several pictures shows

Plate 3

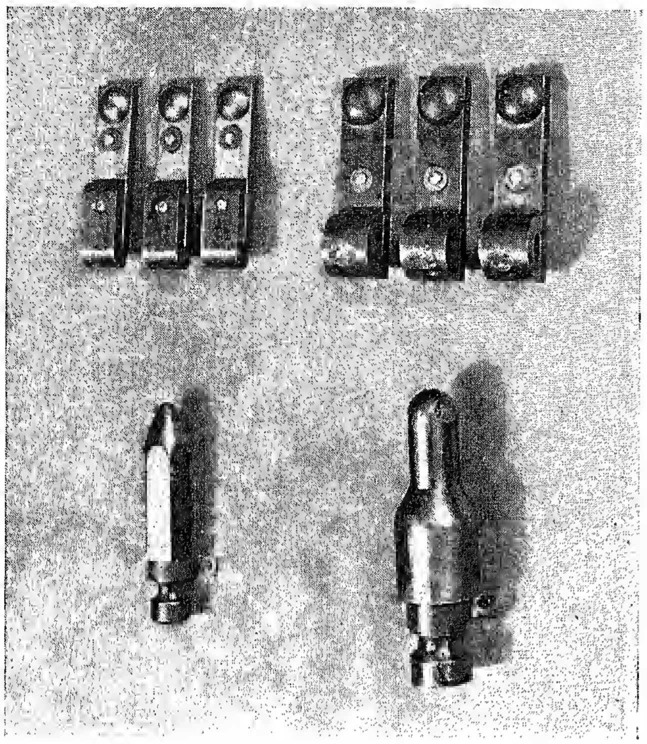


Fig. E.—Comparison of contact wear on equivalent load.

Left-hand. 3 300-volt oil breaker contacts.
Right-hand. 400-volt oil breaker contacts.

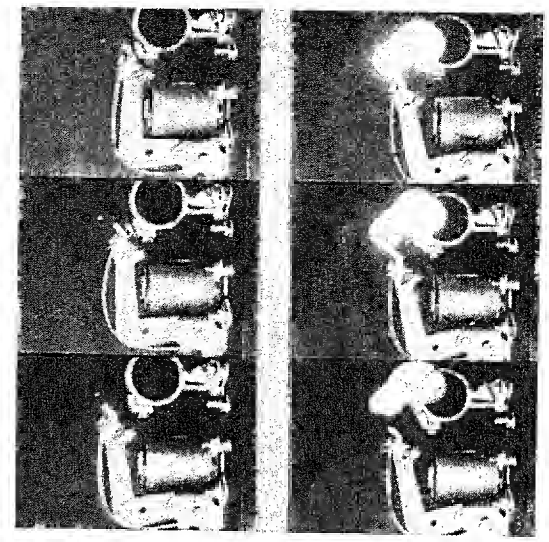
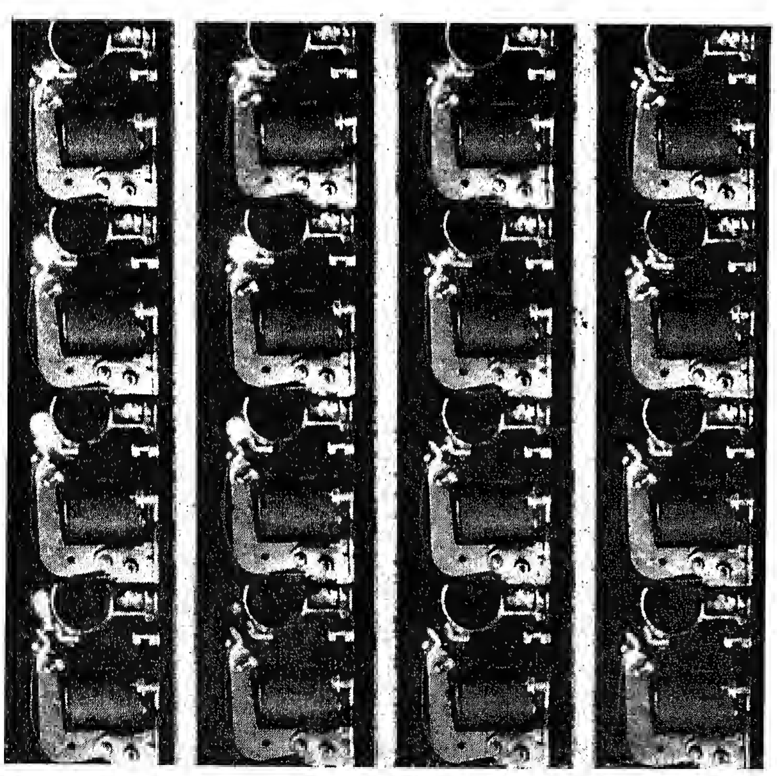


Fig. F.—Portions of slow-motion films (64 frames per sec.).

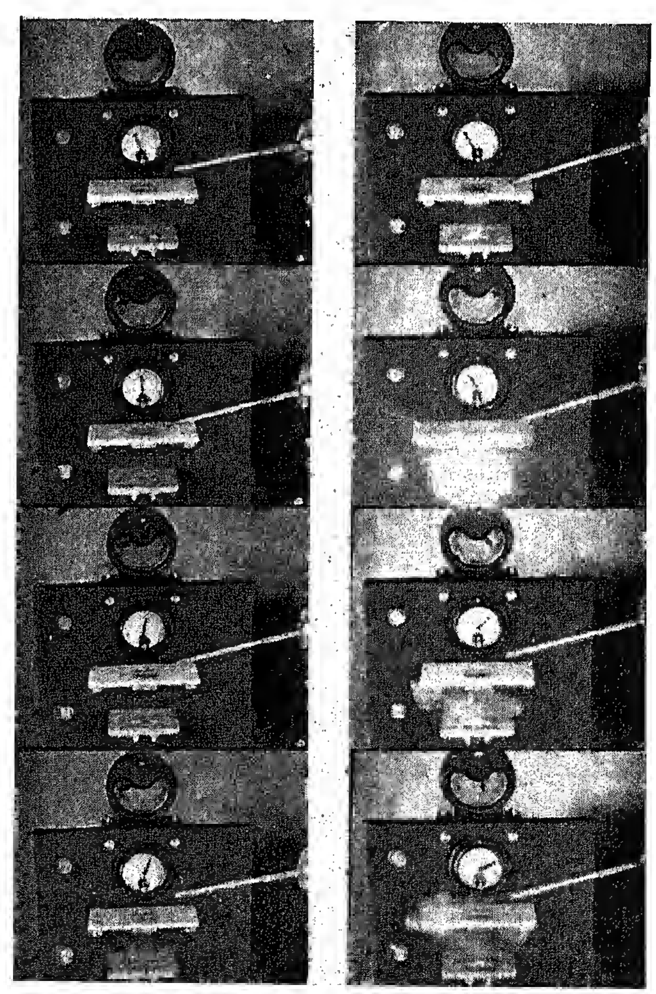
Left-hand. 25 amps., 230 volts, 50 cycles, 0·3 power factor.
Right-hand. 25 amps., 230 volts (d.c.) inductive.
The same contactor (without blow-outs) used in both films.



(1) (2) (3) (4)

Fig. G.—Portions of slow-motion films (64 frames per sec.) of arcing on 5-cycle supply (25 amps., 230 volts).

(1) Break as current rising.
(2) Break at peak current.
(3) Break as current falling.
(4) Break near zero current.



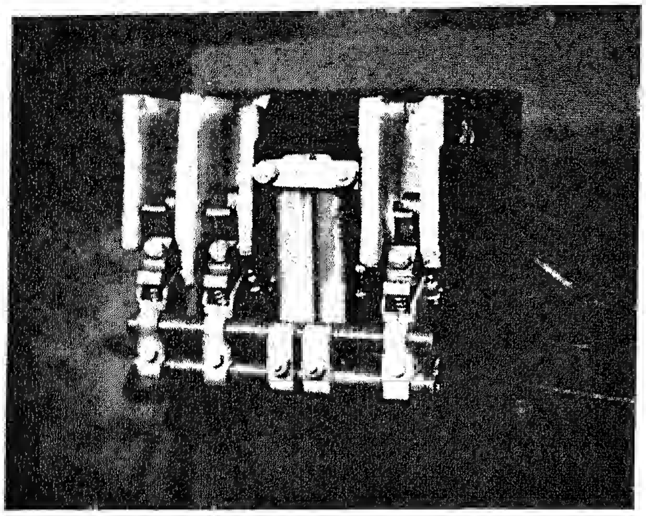
(1) (2)

Fig. N.—Portions of films showing conducting dust accumulating between studs $\frac{3}{4}$ in. apart with 230 volts between studs.

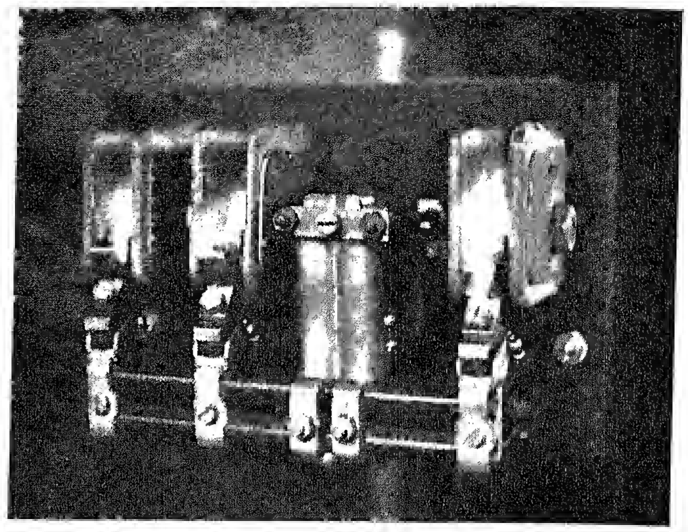
(1) Circuit tripped by 30 mA leakage trip.
(2) Circuit tripped by overload trip set at 25 amps.

(*Facing page* 176.)

Plate 4



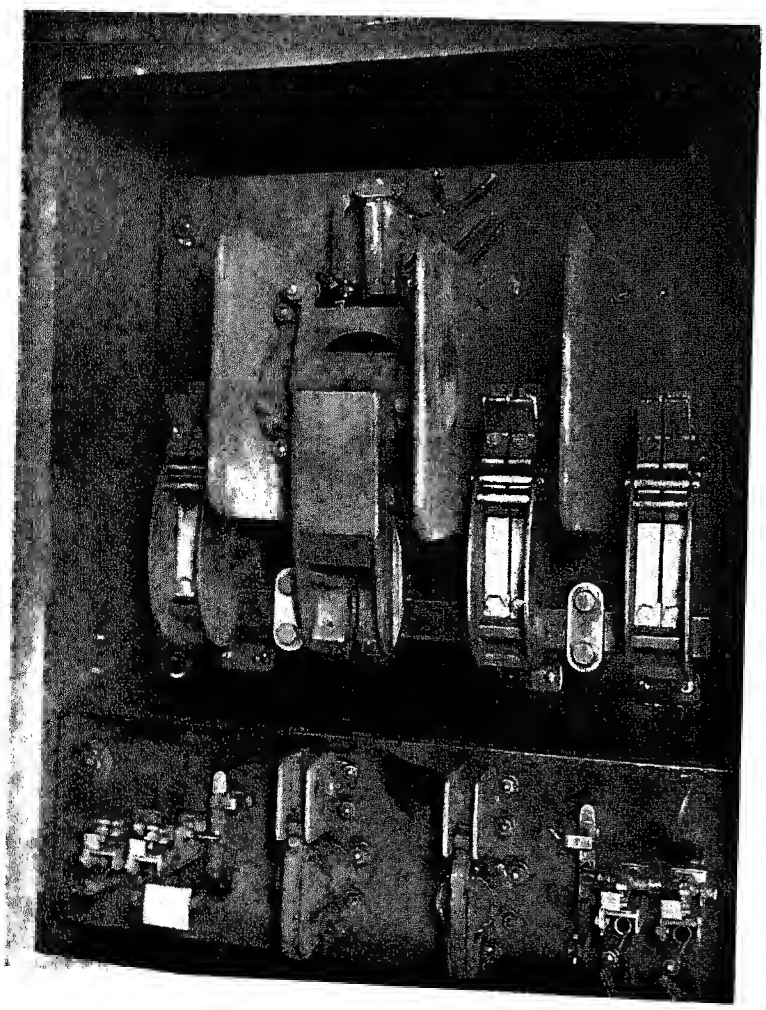
(1)



(2)

Fig. H.—20-amp. a.c. contactors breaking 100 amps. resistance load (camera shutter left open during 5 operations).

(1) Without blow-outs (arc only visible on right-hand butts).
(2) With blow-outs (note increased length of arc).



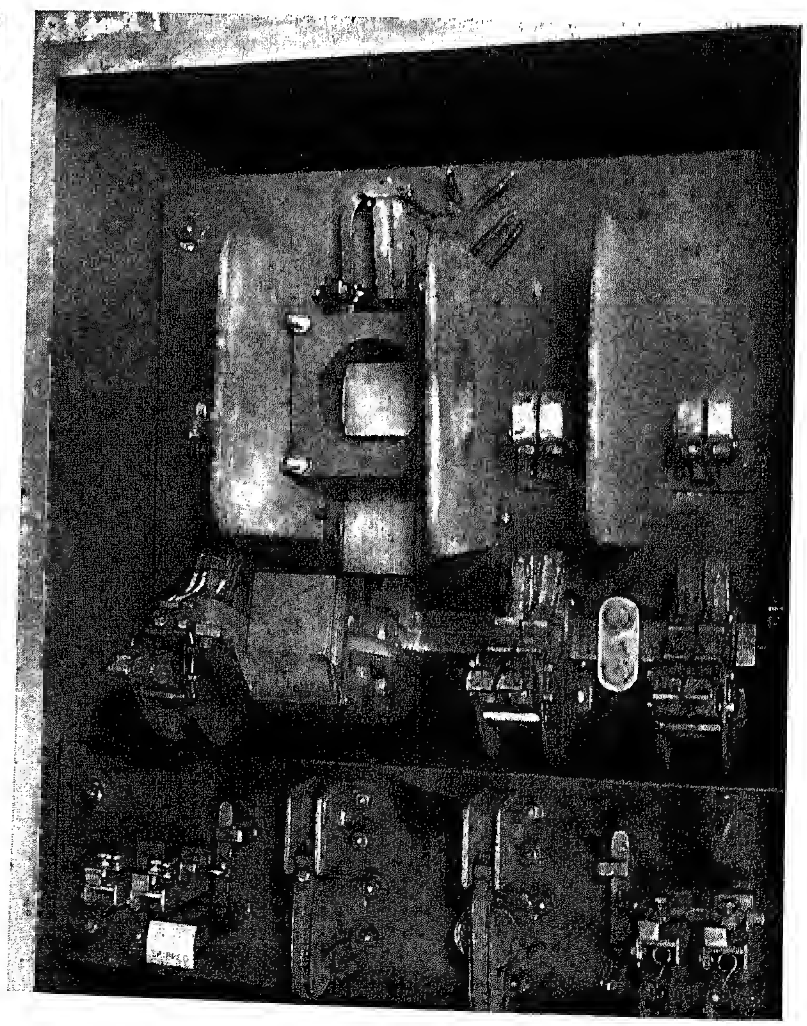


Fig. J.—380-amp. contactor (without blow-outs) after breaking 15 000 kVA and 20 000 kVA (both at 380 volts, 50 cycles, 3-phase, 0·15 power factor).

[Note.—In right-hand view contactor armature is opened out to show condition of contacts.]

the position the moving contact would take if there were no fixed contact for it to hit.

Rupturing Capacity of Starters

Mr. Clothier mentions two important points that bear on this subject; (1) the need for safe apparatus " in close proximity to persons," and (2) the economic importance of continuity of process.

Mr. Mann does not see an easy solution of the problem of rupturing capacity in motor circuits. He goes on to say that 95 % of the purchasers of small starters ignore the problem. If ninety-nine " need no repentance " we must try to save the hundredth from the risk of personal injury. With regard to Mr. Mann's second alternative, I am very doubtful whether a starter can be destroyed internally without serious chance of external damage, and I prefer the view of Mr. McCandless that if a starter is not capable of performing its job it should not be installed. I also agree with Mr. McCandless that a (large) circuit breaker does not ensure the safety of a small motor starter in the event of a severe short-circuit—25 000 kVA can do a lot of damage even in 0·2 second. As Mr. Lloyd says, standard commercial starters are not suitable for such duty, and small starters in particular are best backed up by high-rupturing-capacity fuses. Even if, on the intermediate values of short-circuit mentioned by Mr. Mann, the starter contacts should commence to open before the fuse clears, the damage would be slight and would not endanger the starter operator. This is confirmed by considerable experience within my knowledge, backed by a study of the operating times of fuses and of starters fitted with overload trips.

With regard to larger starters, where protection by circuit breakers might be preferred, Mr. Waggott argues that it requires a very good switch or contactor to stand up to (i.e. merely *to carry*) a fault of 15 000 kVA for the short time necessary for the back-up protection to clear the circuit. Since the discussion in Newcastle I have had the pleasure of showing Mr. Waggott a 380-ampere contactor carrying a fault of 15 000 kVA (380 volts) for $2\frac{1}{2}$ seconds (the contactor and its contacts being in satisfactory operating condition after the test), and I accept the compliment implied in advance by Mr. Waggott's statement.

Mr. Clothier distinguishes between the capacity of the starter to break overloads and the capacity of the back-up protection to break fault currents. Mr. Wilson and Mr. Taylor make the same point in detail. Mr. Butcher asks for further demarcation between main switchgear (circuit breakers) and sub-distribution gear (fuse-switches). Mr. Jones suggests that the fuses for short-circuit protection should be in fuseboards rather than in the starters, and Mr. Kidd accepts my point that the various protective devices in sequence from the source of supply to the motor should be graded to operate in sequence. In this connection Mr. Clothier, Mr. Solomon, and Mr. Taylor, give different views on the rating of the fuses that should be used to back up the overload trips on the starters, summarized in Table B (as applied to straight-on-started motors only).

I agree with Mr. Clothier that it is better to err on the generous side. Taking the minimum fusing current to be just over 1·6 times the fuse rating, my experience also agrees with Mr. Clothier's.

Replying to Mr. Solomon, I understand that the definition of fusing factor is (minimum fusing current)/(rated current). My factor of 3 to 3·5 is not a fusing factor but (fuse rating)/(motor full load).

Certainly a fuse that will carry its rated load continuously, and blow in a reasonable time on a small overload of the order of 25 % or less would be very useful if at the same time it would not fuse after carrying the repeated peaks of straight-on starting. If the fuse had also high rupturing capacity it could be used in sub-distribution boards behind starters to protect the cable to the starter from short-circuits (a point mentioned by Mr. Clothier) as well as the starter itself. So far as I am aware, such fuses are only available to a limited extent and not for prolonged or very frequent starting of motors of the smaller horse-powers (1 to 5 h.p.) where straight-on starting is most common.

Table B

	Mr. Clothier	Mr. Solomon	Mr. Taylor	Author
Full-load current of motor	x	x	x	x
Min. fusing current	$6x$	—	—	Approx. $6x$
" Instantaneous fusing current "	—	—	$6x$	—
Normal rating of fuse	—	$2\cdot5x$ to $3x$	—	$3\cdot5x$

The protection of such motors from overload at a low cost is now commonly entrusted to thermal-overload trips, regarding which widely different views are put forward in the discussion. Mr. Martin considers the thermal trip " the most widely used form of protection," particularly with squirrel-cage motors. Mr. Waggott considers them " practically useless " and prefers to leave the motors for essential auxiliaries without any but short-circuit protection. Dr. Wilson considers that thermal trips " of robust design " are at least as reliable as the electromagnetic type. Mr. Coldwell uses thermal trips up to $7\frac{1}{2}$ h.p., but finds them unsatisfactory for higher horse-powers. Mr. Scarf considers that the thermal trip has suffered from " cheap and unreliable " designs.

How am I to make from such views a consensus of opinion? My own view is that thermal trips have both helped and been helped by the increased use of squirrel-cage motors for individual drive, etc. It is difficult to design and make a thermal trip reliable *on a commercial*

basis (i.e. so that each one of every batch is accurate at close calibrations), but it is also difficult to make dash-pots for magnetic overload trips reliable *in every installation*. Both these difficulties have been too often ignored rather than faced. Users, buyers, and manufacturers have alike bought experience which has cost more than each class anticipated. The smaller the rated current, the more difficult it is to make an *accurate* thermal trip. If close protection is abandoned, the problem disappears, but so does some of the protection.

I cannot now devote more space to this subject, except for answering particular points. Mr. Scarf asks for the relative merits of thermal and magnetic trips used in connection with fuses. Both are satisfactory if the relevant points also mentioned by Mr. Clothier are carefuly watched. I have had entirely satisfactory experience of standard starters backed by high-rupturing-capacity fuses without using a larger starter, though in special instances I have used a larger starter to keep a high factor of safety. Small starters are saved on heavy short-circuits by the current cut-off of the protecting

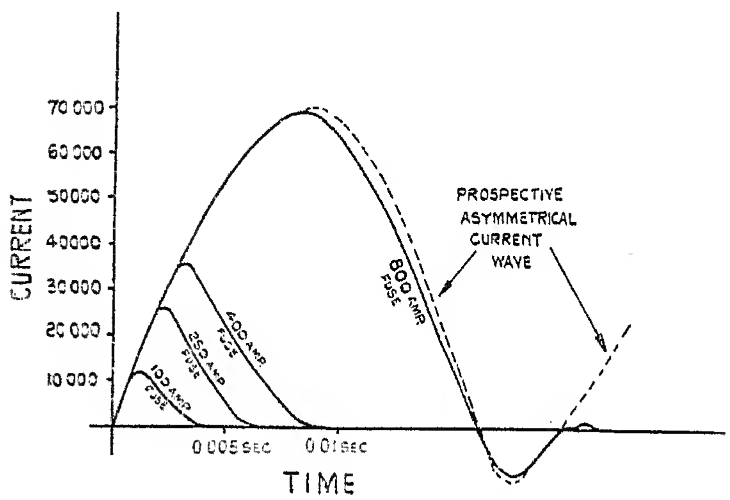


Fig. K.—Diagrammatic illustration of current cut-off by various sizes of fuse when interrupting "prospective" asymmetrical current equivalent to 25 000 kVA, 400 volts, 3-phase, 50 cycles.

fuses roughly summarized in Fig. K and mentioned also by Mr. Lawson. In reply to Mr. Lloyd, either thermal or magnetic trips can be used for most services, if equally well designed. Some thermal trips enable the thermal overload capacity of the motor to be more nearly followed but on services where rapid tripping on overload is required, magnetic trips have, among other advantages, the advantage that an operator believes that there is something really wrong if the starter with magnetic overloads keeps on tripping, but is impatient to "do it again" if a thermal trip gives only one warning.

Thermal trips can be made for any current. Operation by current transformers is an easy solution for large current ratings, but the demand is chiefly for small motors. On larger motors the cost of the overload trips is relatively trifling, and magnetic overload trips with *large* dashpots are satisfactory, though if the starter *must* endure temperatures of 120° F. I would also use a special heavy oil, and also, if the starting peaks are prolonged, magnetic overload trips operated from current transformers with a saturated characteristic on overload.

Mr. Taylor queries B.S.S.587 in regard to the standstill current of a squirrel-cage motor. In an earlier clause of the same specification it is stated that "the ratings of standard a.c. switching starters are based on the assumption that the short-circuit current of the motor does not exceed six times the full-load current." If the figure of six times is exceeded in a particular case, a larger starter

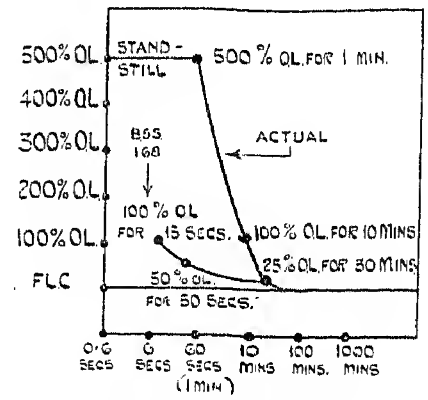


Fig. L.—Overload ratings of motors to B.S.S. 168 and actual (about 10 h.p.).

should be used, or at least a starter having more operating margin than the minimum laid down by the specification.

Dr. Wilson agrees with me that, in regard to the time motors should withstand various overloads, B.S.S.168 is an example of confused wording. A diagram illustrating this point was shown in the slides accompanying the paper, and is reproduced in Fig. L.

Several speakers mention other forms of protection. Mr. Evans and Mr. Jones mention single-phasing troubles. Should the current in the uninterrupted phases be of the order of twice full-load current, as mentioned by Mr. Evans, any ordinary overload trip device would operate without recourse to a phase-balance relay, but the latter is a closer protection, which I have also used, though, in spite of various forms of anti-single-phasing devices on the market, the subject does not seem to be as "live" as my main theme of rupturing capacity, and the same

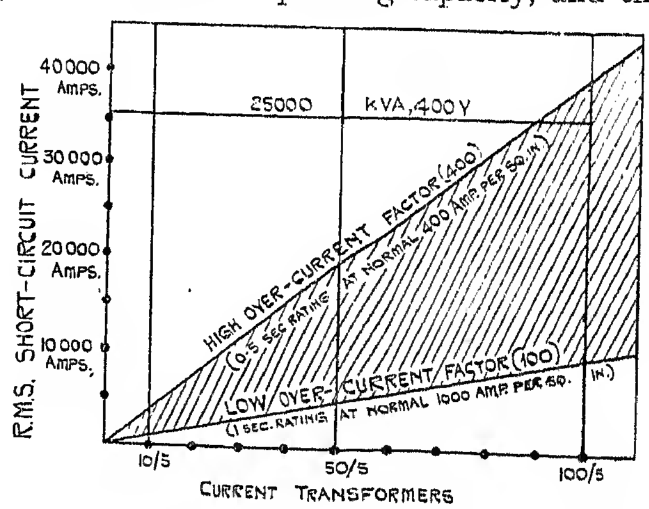


Fig. M.—Diagram based on B.S.S. 81 to show difficulty of designing current transformers of low primary current to withstand short-circuit currents.

applies to the question of using thermal trips built into the motor mentioned also by Mr. Jones as well as by Mr. Butcher.

Mr. Kidd and others have asked me to include in my reply the illustration (now given as Fig. M) included in the reading of the paper at various Centres. Mr. Evans details factors affecting current transformers under

short-circuit. I have obtained and tested special current transformers of 20/5 ratio which would stand 15 000 kVA, 400 volts, for 1 sec. This is a much higher short-circuit current than the 6·6 kV, 75 000-kVA problem (with 10/5 current transformers) mentioned by Mr. Parker. I should like more information than is given in B.S.S.81 on the ability of "commercial" primary-wound current transformers of low rates to stand l.t. short-circuits of 25 000 kVA and upwards *when protected by high-rupturing-capacity fuses* rated at three to four times the primary current. What, if any, damage to the current transformer would be done by the *first* peak current? I have admittedly not made extensive tests, but I have had no trouble in service and agree with Mr. Parker that fuses protect the current-transformer primary windings more speedily than a back-up circuit breaker.

Fuses

I refer in the paper to the wide gap between the B.S.I. ratings of "ordinary" (i.e. semi-enclosed non-cartridge) fuses and the ratings associated with high-rupturing-capacity fuses (12 500 to 25 000 kVA and upwards). Mr. Leeson mentions that "the need has long been recognized," and Mr. Solomon supports him. That this wider specification was still in preparation when the paper was written justifies perhaps further comment.

Mr. Mellonie's figures are interesting when compared with Mr. Leeson's, as in Table C.

Table C

Max. prospective current (amps.)	Mr. Leeson's representative duty	Mr. Mellonie's example
1 000	House service	
4 400		Residence in suburban area
4 000	Light industrial	
10 700		Small factory
13 500		500-kVA transformer substation
16 500	Heavy industrial	
33 000	Power station	
44 000		Substation with two 1 000-kVA transformers

It should be noted that the greater part of the impedances in the typical example mentioned by Mr. Mellonie are in the h.t./l.t. transformers and in the l.t. cables, and that the impedances on the h.t. side only materially affect the highest of the four currents he mentions.

Agreeing with Mr. Clothier, Mr. Leeson, and Mr. Lawson, that any fuse in a 3-phase supply may have to clear at full line voltage we can translate Mr. Leeson's current ratings into kVA ratings as shown in Table D for fuses of 440-volt (not 250-volt) rating.

I have been taken to task by several speakers for mentioning 3-phase fuse tests, but I am quite unrepentant. Having already in the paragraph under Table 2 pointed out that the three fuses in a 3-phase circuit may not blow under similar conditions, I may be supposed to recognize some of the distinctions between 3-phase tests and tests required to prove the ability of the fuses to rupture under the worst conditions. Whatever tests are laid down, however, I would emphasize that they are to prove the suitability of the fuses for practical working conditions. I have pointed out that to specify a d.c. test is to specify something too remote from this practical question. A 3-phase test repeated a number of times would be nearer the practical condition, but I am quite ready to agree that such a test is not near enough or accurate enough. Always, however, a relation must be established between the selected test basis and the practical question—"I am told that the (3-phase) circuit is calculated to give a short-circuit of so many kVA. Will three fuses whose individual rated breaking capacity is so many amps. (or kVA) safely protect this circuit on any possible fault?" Manufacturers still differ in their reply to this question.

Table D

Category	Duty	Current rating (amps.)	Corresponding kVA in 3-phase circuit	
			400 volts	440 volts
1	House service	1 000	690	750
2	Light industrial	4 000	2 750	3 000
3	Heavy industrial	16 500	11 500	12 500
4	Power station	33 000	22 500	25 000

Regarding testing plant for fuse tests, I do not suggest, as Mr. Scarf supposes, that special testing plant is not necessary. I only say that a *large* testing plant is not necessary to obtain short-circuits of 5 000 kVA on fuses. A 1 500 000-kVA testing plant will give 30 000 kVA on 400 volts in spite of the impedances in the test circuit, but in industrial sub-circuits short-circuit values of 2 000 kVA to 5 000 kVA are common and performance data on these values (backed by oscillographs) are scanty.

Mr. Scarf deprecates the use of a storage battery for getting information on a.c. performance and for my reason—"the results cannot be relied upon to be comparable with those obtained in practice." In spite of the plea by Mr. Higgs that d.c. tests are consistent and a.c. tests variable, I prefer Mr. Leeson's suggestions for a.c. testing for a.c. data, and Mr. Lawson's confirmation.

In reply to Mr. Lloyd, I have had experience with testing for high rupturing capacity with a d.c. battery. The battery was a large one, but was never quite the same afterwards.

Mr. Morgan mentions mercury fuses, but I considered that the scope of the paper was wide enough without referring to them.

With regard to over-voltages, Mr. Gosland's and Mr. Farrer's remarks are pertinent. Air-break circuit breakers fitted with blow-outs may also produce over-voltages, and I have known several installations where flash-overs and breakdowns of insulation have occurred mysteriously —perhaps from over-voltages impressed on the system at a point remote from the point of breakdown.

Mr. Lawson comments also on smoke from cartridge-fuse indicators. Satisfactory tests have, however, been made on fuses of the type criticized by short-circuiting the fuse (fitted with indicator) in a metal case filled with dense fumes caused by burning inside the box a large quantity of the powder used in the indicator—a severe test. The suitability of the indicator on short-circuit is also proved by the ordinary tests of short-circuit rating on fuses fitted with indicator.

Table E

Test Circuit. 2 750 volts 60 cycles,
" Prospective " r.m.s. current 26 500 amps. (corresponding to 125 000 kVA, 3-phase),
" Prospective " asymmetrical peak current 70 000–80 000 amps.

Test No.	Fuse rating	Max. peak current	Duration of short-circuit
	amps.	amps.	sec.
1	60	20 000	0·0054
2	125	23 000	0·0098
3	180	38 000	0·0066

Mr. Mellonie and Mr. Thornton comment on Fig. 11. The currents in Fig. 11 are r.m.s. values; and where the time is so short that the r.m.s. value cannot be taken directly from the current oscillogram the " prospective " r.m.s. value is taken, i.e. the r.m.s. current that would flow if the fuse were replaced by a solid link. The curves in Fig. 11 are plotted from over 100 actual tests.

Mr. Clothier asks for proof by test of the 3 300-volt fuses shown in Fig. 5. Although this arrangement was not confined to any make of fuse, the particulars of tests given in Table E show the cut-off effect referred to elsewhere (see Fig. K) in connection with l.t. fuses.

In tests with a 200-amp. circuit breaker in series with three fuses, the circuit breaker tripped simultaneously with the blowing of the fuses, but no current was broken on the breaker contacts. Further tests show that a circuit breaker of low rupturing capacity in series with three fuses can be used to *make* the short-circuit with only slight pitting on the sparking contacts.

Mr. Butcher asks why others taking part in the discussion wish to reduce the short-circuit values of l.t. systems to 12 500 kVA when fuses capable of rupturing a circuit of 25 000 kVA and upwards are available. The circuit which can give 25 000 kVA has usually to be fed through switchgear of over 1 000 amps. capacity above the usual ratings of fuses, and hence the problem affects the incoming switchgear perhaps more than the fuses. Apart from this, however, I agree with those who would prefer to keep the kVA down to ensure a high factor of safety.

Short-circuit Ratings of Circuit Breakers

My argument that 1 500 amps. is the economical limit of size for 400-volt circuit breakers is supported by Mr. Clothier, because he regards 30 000 kVA as an economical limit of breaking capacity on this voltage (in which figure he is supported by Dr. Wilson).

The remarks of various speakers can be summarized as in Table F.

The figures in brackets are filled in approximately and it will be noted that where the main l.t. breakers are over 1 200 amps. I have been kind in my assumed figures for fault kVA and have allowed higher reactance than the 5 % postulated by Mr. Clothier.

I agree with Dr. Wilson that the short-circuit capacity is nearly doubled if in a system supplied by two transformers, both are in circuit instead of one " working " and one " spare," and in the above figures have assumed the worst conditions in which both transformers are in circuit. This condition may only happen for the short time necessary to change over from one transformer to the other without interrupting supply, but this is just the time when someone is standing close by and, therefore, the worst time for a circuit breaker to " blow up." It is frequently impossible to interrupt supply while changing over and, therefore, impossible to make an

Table F

Speaker	Transformers		Main circuit breakers	Possible fault	Reactance
	No.	Capacity			
		kVA		kVA	per cent
Mr. Clothier	3	500	(800-amp.)	30 000	5
	2	750	1 200-amp.	30 000	5
Mr. Mellonie	2	1 000	(1 500-amp.)	30 000	(6·7)
Mr. Kidd	2	1 000	(1 500-amp.)	(30 000)	(6·7)
	2	2 000	(3 000-amp.)	(50 000)	(8)
Mr. Coldwell	2	1 500	2 500-kVA	(40 000)	(7·5)
	2	2 000	(3 000-amp.)	(50 000)	(8)
Mr. Allcock	2	(2 500)	4 000-amp.	40 000	($12\frac{1}{2}$)
	1	(1 500)	2 500-amp. isolator	30 000	5

interlock compulsory. This interlocking can, however, be arranged by a system of Castell locks or otherwise, where the reduction in fault kVA justifies the prevention of the paralleling of the transformers and where conditions allow a momentary shut-down in changing-over.

I am confirmed in my opinion that 1 500 amps. is an economic limit for 400-volt circuit breakers and (in answer to Mr. Gibbins) that 30 000 kVA is the corresponding economic rupturing capacity. Mr. Gibbins rightly suggests trouble with voltage regulation if the transformer impedance is too high, but his calculation of the impedance of the transformer is surely too hasty. One might have 250 000 kVA short-circuit (not load) on the h.t. side of a 100-kVA transformer and only 2 000 kVA short-circuit on the l.t. side.

In compiling Table 3 (rupturing capacity of distribution circuit breakers), I gave (in the advance copies of the paper) 50 000 kVA to 75 000 kVA as "high" figures for a 400-volt supply. The figure of 75 000 kVA was included to draw the criticism of those who still ask or offer such a rupturing capacity on 400 volts. I have enjoyed the remarks in various Centres on this figure and, having served its purpose, it is omitted from Table 3 as now printed.

In connection with my remarks on the electromagnetic forces set up by the very large currents associated with low-tension short-circuits, Dr. Wilson, Mr. Farrer, and Mr. Thornton, also mention the problem of "making" capacity. As Dr. Wilson says, a 400-volt circuit breaker of 30 000-kVA rating may have to withstand a peak "making" current of more than 110 000 amps., and, as Mr. Farrer points out, this may mean a force of the order of 1 ton on the cross-bar. In this connection I might add that in a recent experiment a latched-in triple-pole contactor was closed on a short-circuit of 15 000 kVA with a peak current of 46 500 amps., and the closing coil, which had an initial pull of 60 lb. and a pull of 520 lb. when the contacts met, was able to close the contactor.

I cannot accept without qualifications Dr. Wilson's statement that "the high breaking capacities often specified are unnecessary, for the simple reason that the reactance and resistance concerned will not in general allow such currents to pass." To summarize the considerations mentioned by various speakers under headings:—

(1) *Reactance problems*:—As Mr. Gosland points out, increased reactance in the transformers or cables helps to reduce the fault kVA, but it also brings in the problem of increased voltage-drop from no-load to full load. It is preferable to keep down the fault kVA by sectionalizing the l.t. network.

(2) *Resistance problems*:—As Mr. Grainge points out, "a cable may fail if its temperature limit is reached before the circuit breaker has had time to do its work." Table G gives the maximum currents which paper-insulated cables will carry without damage for 0·2 sec. (C.M.A. recommendations).

(3) "*Skin Effect*" *problems*:—Mr. Thornton suggests that the impedance of cables rises under short-circuit conditions. Dr. Wilson has himself given, in the discussion on another paper,* interesting data on the distribution of current flux when carrying heavy *normal* currents in busbars arranged in various forms. In a recent publication* data are given for skin effects in busbar arrangements for currents of the order of 3 000 to 4 000 amps., but not for short-circuit currents of the order of 30 000 to 40 000 amps. I myself would like more definite information on the combined impedance of transformer windings, cables, busbars, and even the circuit breaker itself, under heavy-current short-circuits. When set up in a test bay with heavy connections to transformers and to an earthing switch, it is difficult to put a 400-volt circuit breaker through a test exceeding, say, 35 000 to 40 000 kVA, even though the test plant may be adequate to test 1 500 000-kVA circuit breakers. It is not so difficult to pass higher *currents* through a short length of busbar, or a single contact, but the connections from transformers to the circuit breaker on test and through the circuit breaker to the "fault" reduce the kVA recorded very considerably, and a "prospective" short-circuit of 30 000–35 000 kVA at the transformer terminals may not give more than 20 000 kVA through the test connections and the circuit breaker.

Table G

Size of conductor	Current	Corresponding kVA	
		400 volts, 3-phase	3 300 volts, 3-phase
sq. in.	amps.		
0·0225	2 800	1 900	16 000
0·04	5 000	3 500	28 500
0·06	7 500	5 200	42 500
0·075	9 350	6 500	53 000
0·10	12 500	8 650	71 000
0·12	15 000	10 400	85 000
0·15	18 750	13 000	106 000
0·20	25 000	17 300	142 000
0·30	37 500	26 000	—
0·40	50 000	34 500	—
0·50	62 500	43 000	—

(4) *Recovery-voltage problems*:—The study in recent years of recovery voltages by cathode-ray oscillograms has added more knowledge of the difference in severity of different arrangements of circuits giving the same short-circuit kVA. Mr. Clothier points out that "the conditions under short-circuit are so complex that they do not lend themselves to solution by calculation alone." Even in small motor starters, engineers find that designs which have been satisfactory under ordinary conditions are more liable to flash-overs in normal service (not short-circuits) when fed directly from large transformers.

(5) *Arcing problems*:—Low-voltage heavy-current circuit breakers present their own particular problems. Although the arc is short, the heavy current results in the production of arc energy very rapidly while the contacts

* H. W. CLOTHIER: "Metal Clad Switchgear," *Journal I.E.E.*, 1932, vol. 71, p. 285.

* "Copper for Busbar Purposes" (Copper Development Association, 1936), p. 60.

have only small separation, and, as Mr. Clothier says, "the arc itself sets up pressure waves which add to the stresses on the contacts."

It is not only necessary, as Mr. Clothier says, supported by Mr. Farrer, to prove circuit breakers under testing-station conditions. It is necessary also, as Mr. Thornton says, to relate the test conditions to the service conditions to know whether the factor of safety is inadequate or too generous. Mr. Solomon points out that test conditions are *usually* more severe than those in the field. Mr. Gosland stresses the danger of applying the word "usually" to all circumstances, and it is evident in the discussions that, as Mr. Solomon says, "more knowledge of the short-circuit currents actually experienced on factory and domestic premises is urgently required." I would add that it is not enough to know the "currents"—the "conditions" are equally important.

A few speakers comment on my typical figures with regard to time of operation and arc energy of low-tension circuit breakers. Mr. Clothier gives as a general guide a duration of 4 or 5 cycles (i.e. 0·08 to 0·1 sec.) from energizing the trip coils to final arc extinction. Mr. Farrer gives much shorter times (0·02 sec.), which probably correspond to the use of direct-acting overload coils and a tripping action which is considerably accelerated by the electro-magnetic forces.

Mr. Farrer further comments on arc energy, but his argument could not be taken to extremes. Where is the arc energy to come from to make the arc energy of a 33-MVA 440-volt breaker equal (to take an extreme case) to the arc energy of a 500-MVA 6 600-volt breaker in the same time of arcing? If the conditions are similar (not that they are) the short-circuit in the former case is only putting into the circuit 1/15th of the energy of the latter case. I agree that the arc energy is not *proportionately* smaller in the 440-volt breaker, but would suggest that data from 440-volt tests provide a useful check on figures and formulae based on tests at higher voltages, but with smaller currents. For instance, the "usual" average speed of break for 6 600-volt breakers is of the order of 10 ft. per sec. (1·2 in. per half-cycle at 50 periods), but for l.t. breakers with shorter breaks a speed of 3 ft. per sec. (0·3 in. per half-cycle) may be more desirable.

Anticipation of Short-circuits

The comment by Mr. McCandless on my omission to mention earth-leakage relays does not really come under the above heading, nor under any other of the headings already mentioned. Mr. McCandless is, however, quite right in drawing attention to the omission, and I fully agree with his remarks. In a demonstration accompanying the reading of the paper, I showed the comparative operation of an earth-leakage trip set at 30 milliamps. and an overload trip set at 25 amps. (see Fig. N, Plate 3). In the overload trip test the conducting dust burned for a considerable time, the current (top meter scaled 0/2·5 amps.) remaining under 2 amps. until an "explosive" short-circuit occurred. The lower meter (scaled 50/0 megohms) read the insulation resistance, this meter giving a correct reading only when the circuit was interrupted (bottom pictures). In the overload trip test the insulation was broken down completely, but in the leakage-trip test there was only a faint spark before the trip operated, and the insulation could be restored by blowing the dust away.

In reply to Mr. Johnston, I do not know of any practicable method of testing for and finding weak points in the insulation of a ship's wiring without cutting a section out of commission and, as Mr. Johnston says, "disconnecting the lamps, motors, etc., and laboriously testing section by section." It is possible that some extension of present "cable search apparatus" may be an approach to a solution. If one could walk down an alley-way with a portable "radio set" (inadequate description!) and a pair of earphones and check the insulation in the vicinity by "listening-in" for an incipient leakage, the inspection of insulation would be an easier matter. The risk of fire due to the persistence of a slight leakage insufficient to blow fuses or even to show up on a main earth-leakage indicator is not to be despised. Any sensitive central indicator would be subject to the objection that no indication is given as to where the leakage is, and this objection also applies to the scheme set out in Fig. 14 for a 3-phase 4-wire system.

In answer to Mr. Gibbins, this indicator is in the form of a sensitive moving-coil voltmeter (V) of high resistance (VR). A rectifier R provides a d.c. e.m.f. which, when the push-button PB is pressed, is established between the neutral point N and earth. If there is a leakage between any point of the a.c. wiring protected by the circuit breaker CB and earth, a direct current passes through the indicator V, which is calibrated in "megohms in series with the instrument." Thus the insulation of the system to earth is read directly on the instrument in megohms, although the system is "on load"—the d.c. test supply being superimposed on the a.c. system.

The scheme of Fig. 14 is subject to several objections, but is given to stimulate interest in a subject which belongs to the future rather than to the present.

In conclusion, I should like to express my appreciation of the interest taken in the subject of the paper at all the Centres where it has been read. The borderline between motor control gear and distribution gear—which is the line taken by the paper—might not at first seem to be a subject of general interest. I am conscious of the fact that the greater part of the paper applies more particularly to large-scale installations, but I endeavoured to correct this bias, when reading the paper, by giving illustrations and demonstrations of less specialized character.

It is gratifying to find so much support in the discussions for some of my main points, and if interest has been aroused in those aspects on which there are various views, I shall have been well rewarded for my attempt to review a section of the industry rather than any particular manufactures.

A SURVEY OF MARINE RADIO PROGRESS, WITH SPECIAL REFERENCE TO R.M.S. "QUEEN MARY"

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(*Paper first received* 21*st September*, 1936, *in revised form* 12*th January*, 1937, *and in final form* 14*th May*, 1937; *read before the* WIRELESS SECTION 3*rd March*, *and before the* SCOTTISH CENTRE 13*th April*, 1937.)

SUMMARY*

Marine radio may conveniently be treated as a special branch of radio engineering, with its own particular problems and its own technique. No general survey of the field having been published for some time past, this paper has been prepared with a view to placing on record the state of the art obtaining in 1936.

The paper has been divided into four main Sections. In the first of these is given a short summary of progress during the last 5 years, with particular reference to the nature and volume of traffic, the types of communication involved, and the growing use of direction-finding equipment by navigators.

The second Section deals briefly with the types of radio equipment now customarily fitted in cargo vessels and in passenger vessels other than those which come within the "express steamer" class.

In the third Section some account is given of the radio problems encountered in the "express steamer" class of vessel, and of the main equipment items selected to meet the conditions anticipated in the particular case of R.M.S. "Queen Mary."

The last Section deals with the actual radio station of R.M.S. "Queen Mary," as built up from the main equipment items described in the third Section, and their associated power supply and aerial systems, etc. The control-room arrangements, which handle four independent duplex circuits, are given in some detail, together with an account of the special precautions adopted to insure efficient multiplex working, quick change of wavelength, high-speed transmission and reception, and simultaneous communication on both telegraphy and telephony with both sides of the Atlantic.

CONTENTS

* As a matter of convenience the following nomenclature has been adopted throughout the paper to indicate the wavebands allocated to ship radio services.

	Metres	kc.
Short-wave band	13·92–11·72	21 550–25 600
	18·29–16·90	16 400–17 750
	24·39–22·47	12 300–13 350
	27·27–26·32	11 000–11 400
	36·59–33·71	8 200– 8 900
	48·78–44·94	6 150– 6 675
	100–52·63	3 000– 5 700
Small ships' wave band ..	200– 100	1 500– 3 000
	220	1 364
Medium-wave band	822– 583	365– 515
Long-wave band	2 727–1 875	110– 160

(1) REVIEW OF PROGRESS

(1.1). Increasing Use of Valve Transmitters.

The first practical application of radio provided communication with ships at sea over distances and under conditions which make all other forms of communication impossible. More than 35 years have elapsed since that first application, and marine radio still remains unique for this particular purpose, so important to commerce and so essential to safety. *In no other field, except that of air transport, is radio irreplaceable by other forms of communication.* Successive international conferences have recognized this and have therefore been constrained to grant to marine radio facilities and protection which may seem to be out of proportion to the

capital investment and number of users, as compared with those of other services.

From an analysis of the lists of coast stations and ship stations, published by the International Bureau at Berne, for March 1931 and 1936 respectively, Table 1 has been compiled. This gives in condensed form a very fair indication of the progress made during the last 5 years.

It will be observed that in 1930 spark transmitters were in general use, over 86 per cent of ships being so fitted; there were in fact comparatively few ships which did not at that time rely on spark for their normal communication, although quite a number of valve transmitters for long-range working were installed on passenger vessels. The percentage of "spark" ships had fallen to less than 63 per cent at the end of 1935, and will continuously decrease with each year until 1940, when spark equipments of over 300 watts input will be forbidden by international agreement. The inconveniences imposed by spark transmitters on other services, and the advantages presented by valve transmitters, are so universally admitted that the general abolition of the spark set was actually decided on 10 years ago at the International Conference which met at Washington in 1927, but on account of the heavy expenditure involved it was agreed that a 13-year period of grace should be afforded shipowners to make the change.

Table 1

	31st Dec., 1930	31st Dec., 1935
Total number of ships (excluding warships) fitted with radio ..	14 001	14 813
Fitted with spark only	11 561	8 418
Fitted with valve only	1 423	3 471
Fitted with arc only	57	—
Fitted with spark and valve } Fitted with spark and arc }	573	856 (no arcs)
Fitted with wireless telegraphy and radiotelephony	193	982
Fitted with radiotelephony only	194	988
Fitted with radio direction-finder	2 938	5 163
Fitted with wireless telegraphy (spark and valve) and radiotelephony	—	66
Fitted with radiotelephony and spark	—	32

Small spark transmitters meeting the minimum requirements of the Safety of Life at Sea Convention and having an audio-frequency input to the supply transformer of less than 300 watts will still be permitted indefinitely, but these too will probably eventually disappear in the ordinary course of events. It is estimated that about 3 000 ships altogether are equipped with spark sets of less than 300 watts, which leaves some 6 000 ships whose equipment must be modified before 1940.

Apart from the progressive replacement of "spark" by "valve" there have been three new developments in marine radio since 1930, and two of these—world-wide communication on short wave for ocean-going vessels, and short-distance radiotelephone communication for coasters and fishing vessels—are of considerable importance to shipowners. The third development—that of linking up ships at sea with the international telephone service—though perhaps the most spectacular, is at present confined to a small number of the larger passenger liners.

(1.2). Short-wave Communication.

The great advantage of short-wave equipment to the shipowner lies in the remarkable ranges obtained by simple inexpensive apparatus of no greater power than is required for the standard installation of the average cargo vessel.

For example, a British ship equipped with short wave and on voyage in any part of the world is practically certain of being able to place herself, either directly or through some other similarly equipped ship, in touch with her owners through the Post Office Radio Station at Portishead at least once in every 24 hours. In this way cargoes can be diverted, destinations changed, and repairs and ships' business generally facilitated with a minimum of delay and expense.

The Post Office Guide indicated that in January, 1930, there were 222 ships notified as being equipped with short-wave radio and likely to communicate with Portishead. In January, 1937, the number had increased to 700, whilst the short-wave traffic at that station has grown in the same period from less than 300 000 paid words per annum to over 2 000 000. In 1930 the Post Office maintained only a single position for short-wave traffic; to-day there are no less than 12 positions which can be manned during periods of heavy traffic.

(1.3). Short-distance Radiotelephone Service.

In 1930 there were no British vessels fitted with radiotelephony. To-day there are nearly 1 000 coasting and fishing vessels operating radiotelephony on frequencies in the small-ships' waveband. In fact there are so many vessels operating radiotelephony in a comparatively restricted area that the Administrations of Great Britain, France, Belgium, Holland, Denmark, Germany, Norway, and Sweden, called a conference in 1934 which resulted in what is known as the "North Sea Regional Arrangement." The example thus set has been followed in other localities, such as the Baltic and the South-Western area of Europe. Under this arrangement definite wavebands —15 to 20 kc. wide for land stations and 25 to 30 kc. wide for ship stations—are allocated to each country for short-distance ship-shore radiotelephony, and the Administrations undertake that vessels licensed by them shall comply as soon as possible with the technical requirements and recommendations of the Madrid Convention.

These equipments are usually to be found on ships which are not compulsorily fitted (i.e. of less than 1 600 tons gross) as well as in the fishing fleets, and are evidence of the increasing importance attached by shipowners and others to the communications of their vessels. Such equipments are of quite small power, usually about 50 watts in the aerial, but are remarkably effective, as well as being simple to operate and maintain. Their range is nominally about 150 miles over sea, though this distance is often greatly exceeded in practice.

With the co-operation of the Post Office, which Department made the necessary provision at their coast stations, a British radiotelephone organization has been built up, not only for trawlers but also for coasting and other vessels of small tonnage. All Post Office shore stations now make provision for radiotelephony, although messages must be passed in the form of radiotelegrams, as is done in the case of the phonogram in the inland telegraph service. At the Seaforth and Humber radio stations, exceptionally, provision is made for the speaker on board the ship to converse directly with any telephone subscriber in Great Britain—the service is, however, carried out by simplex or one-way working, and is therefore only suitable for persons who are accustomed to, or at least instructed in, that method. Some idea of the rapid growth of the small-ship radiotelephone service may be gathered from the figures for Great Britain given in Table 2.

Table 2

	1930	1931	1932	1933	1934	1935	1936
Radiotelegrams sent by radiotelephone on small-ships' band (words)	—	—	51 000	103 000	168 000	216 000	253 000
Ships less than 1 600 tons equipped with radio transmitters and operating on small-ships' band	466 (Practically all spark)	528	597	709	868	979	1 155 (971 having radiotelephony)

(1.4). Subscribers' Radiotelephone Service on Liners.

This service was first put into operation on board the White Star liner "Majestic" in 1930, and from a technical point of view has been of great interest. Owing to the nature of the service the charges are necessarily high and the public a very restricted one. It is of interest, however, to record that, as a demonstration of the co-operation possible between the international radio and land-line telephone services, an aviator in flight in Argentina was on one occasion placed in direct telephone contact with the captain of the "Majestic" at sea in the North Atlantic. The speech was passed by radio from Argentina to Spain, through the land lines of Spain, France, and Great Britain, and from Great Britain by radio again to the "Majestic." There are at present 23 ships fitted with subscribers' service radiotelephony, and its popularity with the public may be judged from Table 3.

(1.5). Distribution of Traffic with Wavelength.

Fig. 1 is a record of the ship and shore radio traffic handled by the Post Office for the years 1925–1936 inclusive. It will be observed that the traffic has increased by about 66 % in the last 3 years.

Broadly speaking, this traffic comes under two distinct categories; (*a*) messages sent on the service of the ship, and (*b*) messages sent by the general public.

Telegraph traffic in the medium-wave band is over (relatively) short distances and consists chiefly of cargo vessel communications, whilst that in the long and the short-wave bands is long-range traffic and covers most of the passenger vessel communication. The increasing number of cargo ships equipped with short-wave telegraph installations for world-wide communication has in recent years considerably augmented the short-wave traffic.

The medium-waveband traffic has remained remarkably constant, as might be expected from the nature of the communications. The long-waveband traffic, however, fell appreciably in the early stages of the financial depression following the reduction in the passenger movement on the North Atlantic—the area which it chiefly served. Such recovery as might have been expected recently has been masked by a tendency to substitute short-wave for long-wave communication when well within the range limit of the latter, thus adding to the congestion in the short-wave band. This is an undesirable feature since it is evidence that wireless operators are not making economical use of the facilities at their disposal. The short-wave ship and shore channels, which are world-wide in their sphere of operation, are already becoming congested and should be retained as far as possible for use only when communication is not possible on the medium and long wave channels.

Table 3

Date	Number of ships fitted with Atlantic ship-to-shore service*	Calls through London terminal
1930	4 (3 British)	351
1931	6 (5 British)	276
1932	5 (4 British)	371
1933	10 (6 British)	733
1934	12 (7 British)	1 102
1935	22 (7 British)	1 176
1936	23 (6 British)	2 151

* See "Post Office Guide."

The amount of actual traffic handled by individual ships varies very greatly. Many cargo ships only handle one or two messages a month. At the other end of the scale are large passenger liners which, on the voyage to New York and back, may pass anything between 5 000 and 15 000 words of paid traffic as well as some 15 to 25 radiotelephone calls.

The "Queen Mary" on her maiden voyage to New

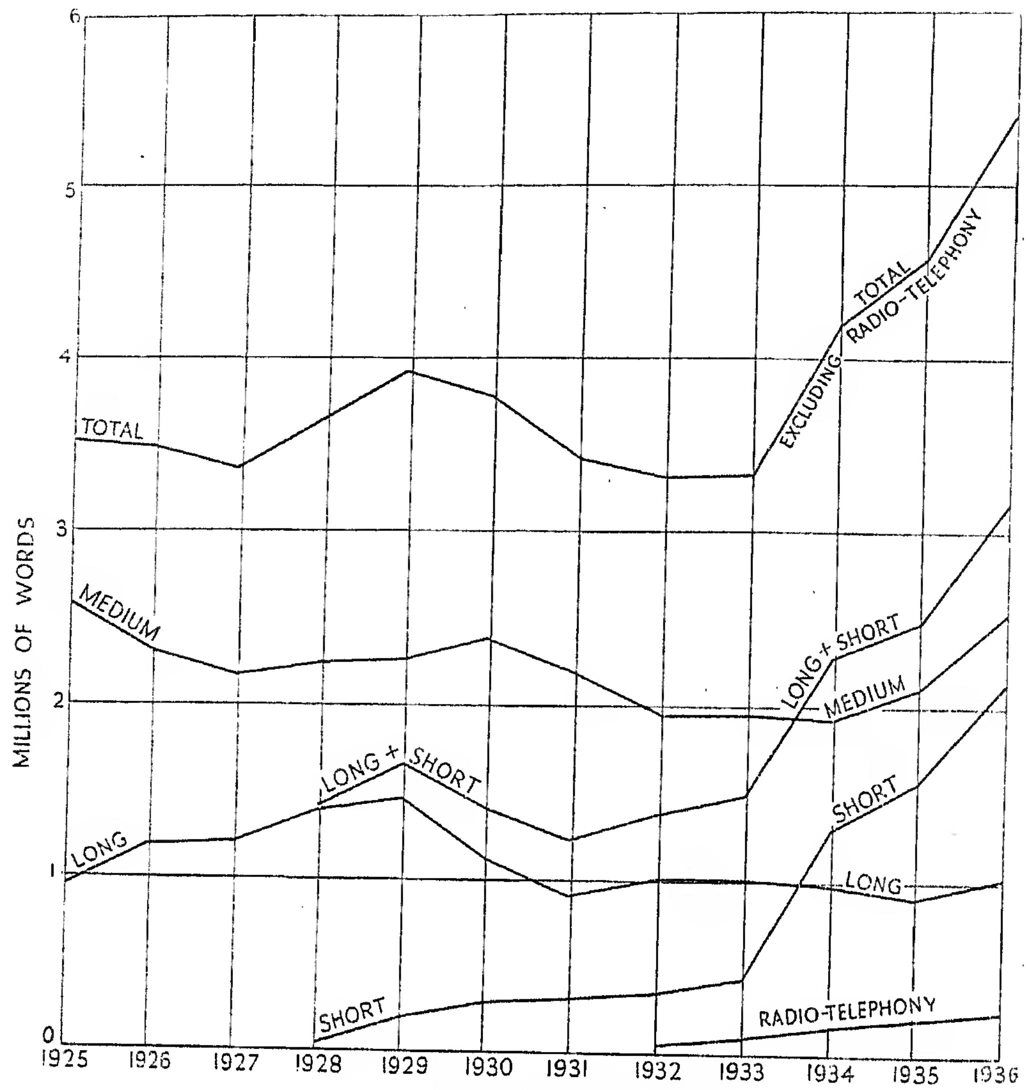


Fig. 1.—Traffic analysis, 1925–36.

York and back is believed to have created a record in this connection. During the round trip the radio traffic handled was as follows: 175 000 paid words of telegraph traffic, 291 radiotelephone calls, and 11 hours 32 min. of broadcast programmes. Such an occasion was, of course, quite exceptional and can only be expected to recur at rare intervals.

(1.6) International Conferences.

Since the Washington Convention in 1927 there have been several international radio conferences—the Madrid Conference, which drew up the International Telecommunications Convention in 1932, and the International Radioelectric Consultative Committee (C.C.I.R.) Conferences at The Hague in 1929, at Copenhagen in 1931, and at Lisbon in 1934, for the study of technical questions of international importance.

Apart from the allocation of frequency bands to the different services—a difficult task in itself and made the more difficult by its semi-political nature—the most important and far-reaching agreement technically has been the definition of limits of tolerance and stability for transmitters. The final recommendations for the mobile services are set out in Table 4, frequency tolerance being defined as the maximum divergence admissible between the assigned frequency and the actual frequency, while frequency instability is the maximum admissible divergency resulting solely from slow variations of the

Table 4

	Frequency of transmitter							
	10–550 kc. (30 000–545 m.)		550–1 500 kc. (545–200 m.)		1 500–6 000 kc. (200–50 m.)		6 000–30 000 kc. (50–10 m.)	
	Tolerance	Instability	Tolerance	Instability	Tolerance	Instability	Tolerance	Instability
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
Mobile stations using indicated frequency ..	0·5				0·1		0·1	
Mobile stations using any wave within the band		0·5*		0·5		5 kc		0·1 0·04†

* It is recognized that many spark and auto-oscillator transmitters cannot comply.

† If and when shared with fixed stations.

frequency of the transmitter. Frequency tolerance is applicable to any station which is using a specific indicated frequency, and frequency instability is applicable to a station using any wave within the band of waves allotted to its use.

(1.7). Safety of Life at Sea.

Time and space do not permit reference in any detail to conditions to be fulfilled by the radio installation on board a compulsorily equipped British ship for the purpose of safety of life at sea, but those who are interested will find these conditions fully described in the Board of Trade pamphlet: "Instructions to Surveyors as to Wireless Telegraphy, Circular 1686 of 1932."

Briefly, all ships over 1 600 tons (gross) and all passenger vessels must be equipped with a simple radio installation capable of communicating on frequencies of 500 kc. (600 metres) and 375 kc. (800 metres, spark or I.C.W.) over at least 100 miles by day over sea.

A radio direction-finder, approved by the Administration to which the ship is subject, must be installed on all passenger ships of 5 000 tons (gross) and upwards. The utility of the radio direction-finder is, however, of far more than a purely emergency nature. Such equipment is viewed to-day not so much as a compulsory fitting but as a normal aid to navigation. It is accordingly dealt with from this standpoint in sub-section (1.81).

(1.71). Auto-Alarms.—A brief reference to the auto-alarms and alarm signals seems desirable in view of the fact that this substitute for human watch has been agreed to internationally. The desirability of keeping constant watch on board all ships for the distress signals of a ship in difficulties is universally recognized, but it is equally evident that such a watch involves the whole-time employment of at least three men and is therefore an expensive arrangement except in the case of large passenger vessels where such a staff is required for the handling of radio traffic for the general public.

The story of the inception and introduction of the auto-alarm on British ships has been told by Major Binyon in his address as Chairman of the Wireless Section in March 1926.* The British delegation to the International Radiotelegraph Conference at Washington (1927) called attention to the possibilities of such a device and obtained international recognition of a signal—consisting of twelve 4-sec. dashes separated by 1-sec. intervals—to be called the "Alarm signal," and which would preface the "Distress signal" (SOS) proper. Subsequently the International Safety of Life at Sea Conference which met in London in 1929 agreed to recognize the auto-alarm as a substitute for human watch and decided that a ship which carried one certified wireless operator and an approved auto-alarm would fulfil all requirements as far as a watch for the distress signal was concerned.

At the end of August, 1936, there were 1 902 ships in the world fitted with an auto-alarm, and of these 1 036 were British.

The alarm signal was intended to be transmitted by the operator, using an ordinary morse key and timing his transmissions by the seconds hand of a watch or clock, but it is obvious that under very trying conditions the accuracy of the timing of the signals may be impaired.

* *Journal I.E.E.*, 1926, vol. 64, p. 83.

As the final success of the auto-alarm depends quite as much on the accuracy of transmission of the alarm signal as on its good reception, a number of ships are now equipped with an automatic key for the transmission of this signal. The Post Office also has installed such a key at all British coast stations.

(1.72). Lifeboat Equipment.—Two other radio subsidiary equipments are taken into consideration by the Safety of Life at Sea Convention. These are the lifeboat radio installation and the radio direction-finder. Major Binyon gave a full description of a lifeboat set in the address referred to above, and the requirements have changed very little in the past 10 years.

In all ships which carry 13 or more lifeboats a prescribed number must be provided with a radio-telegraph installation, the range and efficiency of which on 600 metres (the International Distress wavelength) has been approved by the Administration concerned. In Great Britain the equipment must be of the "spark" type, the aerial must have a minimum height of 22 ft. above the water-level, and the power must be sufficient to give a minimum output of 10 "metre-amperes"* with a single-wire aerial. It is understood that the Board of Trade are prepared to accept valve transmitters in lifeboat equipments as soon as they are satisfied that these can be made equally as robust and reliable as spark transmitters. The Board are also considering the application of radiotelephony in this connection and, in the case of the "Queen Mary," have approved the experimental installation of a small radiotelephone transmitter in addition to the radiotelegraph equipment.

(1.8). Aids to Navigation.

(1.81). Radio Direction-Finders.—The radio direction-finder has been for many years regarded as part of the radio installation for operation by the wireless staff, but during the last two or three years there has been a tendency to regard it as a navigational instrument for operation by the navigating staff. This tendency is an interesting one and is due to several causes:—

(1) The extension of the beacon system and the international interest which has been taken by the competent authorities of all maritime countries to render it as simple and reliable as possible.

(2) The simplification of the radio direction-finder not only as an instrument but also in the manner of its use.

(3) The spread of broadcasting, which has rendered tuning-in and reception of radio signals familiar to almost everyone.

The radio direction-finder found on board ships of the Mercantile Marine is of one or other of two types. One is the Bellini–Tosi type utilizing two fixed loop aerials at right-angles to each other, and the other the type employing a single rotating loop. There is little to choose between the two types as regards accuracy, but on the whole the rotating-loop type is perhaps the more convenient to install and use as a bridge instrument equipment for the navigating officer, and especially so in new tonnage where provision can be made for it in the plans of the ship. The fixed-loop Bellini–Tosi type, however, will

* "Metre-amperes" is a temporary empirical expression adopted internationally as a guide to the range of an equipment. It is the product of the actual height in metres of the aerial from its highest point to the water line and the current in amperes measured at the base of the aerial.

continue to be found on board many ships as it has the advantage that the position of the loop is to a considerable extent independent of the position of the receiver.

In ships fitted with a gyro-compass it is possible to combine a compass repeater with the scale of the direction-finder; this is of advantage to the observer as he is able to obtain the true bearing of the transmitting station directly from the instrument without reference to another observer at the standard compass.

While it is impossible to detail here the wide variety of form in which the radio direction-finder is manufactured, the following examples are of particular interest as dealing with equipments which have been specially designed to meet the needs of the navigating officer.

In the first type simplicity in operation and economy in cost have been the principal considerations in the design. In the second type cost has not been an important consideration, and certain refinements have been added which, together with a more elaborate design, make it suitable for installation in particular vessels. Both types have received the approval of the Board of Trade and Post Office for installation on board those ships which by law are required to carry direction-finders.

Fig. 2 illustrates the simpler type of direction-finder. This instrument is extremely easy to install and operate, and it will be seen that it takes the form of a single self-contained unit, although it is actually supplied to the ship in three parts which are bolted together on installation.

The loop consists of a single-layer coil $22\frac{3}{4}$ in. diameter, wound inside an earthed screen of copper tube and hermetically sealed inside the latter; it is rotated by a vertical hollow shaft passing down through the pedestal and receiver to the handwheel below. A horizontal 0°/360° illuminated scale is mounted on the lower end of the shaft, and indicates the bearing of the required station against an index mounted inside the receiver and viewed through a window in the front panel. Slip-rings, to which the ends and centre of the loop are connected, are also mounted on the rotating shaft, and collector brushes serve to pass the received signal to the receiver.

The receiver is of the tuned radio-frequency type employing four valves—two h.f. pentodes, detector, and l.f. pentode. The loop and receiver circuits are simultaneously tuned by a single dial.

Sense (or elimination of the 180° ambiguity common to all direction-finders) is obtained by coupling a short vertical aerial to the input circuit. This vertical aerial is also used very successfully to eliminate bad minima due to the out-of-phase signal set up by the ship's structure.

Fig. 3 indicates diagrammatically the second type of rotating-frame radio direction-finder; this is the type installed on the "Queen Mary." It is of the binnacle type carrying a single rotating loop which occupies a position on the superstructure near the standard compass. The binnacle is installed in a special compartment immediately beneath the loop and adjoining the compartment containing the master gyro-compass. The compartment containing the binnacle is lined with copper sheeting. The operation of the radio direction-finder by the navigating officer is completely independent of the operation of the radio installation by the wireless staff, and the former can at any time take bearings without the necessity for any reference to the latter. The instrument may be briefly described as follows:—

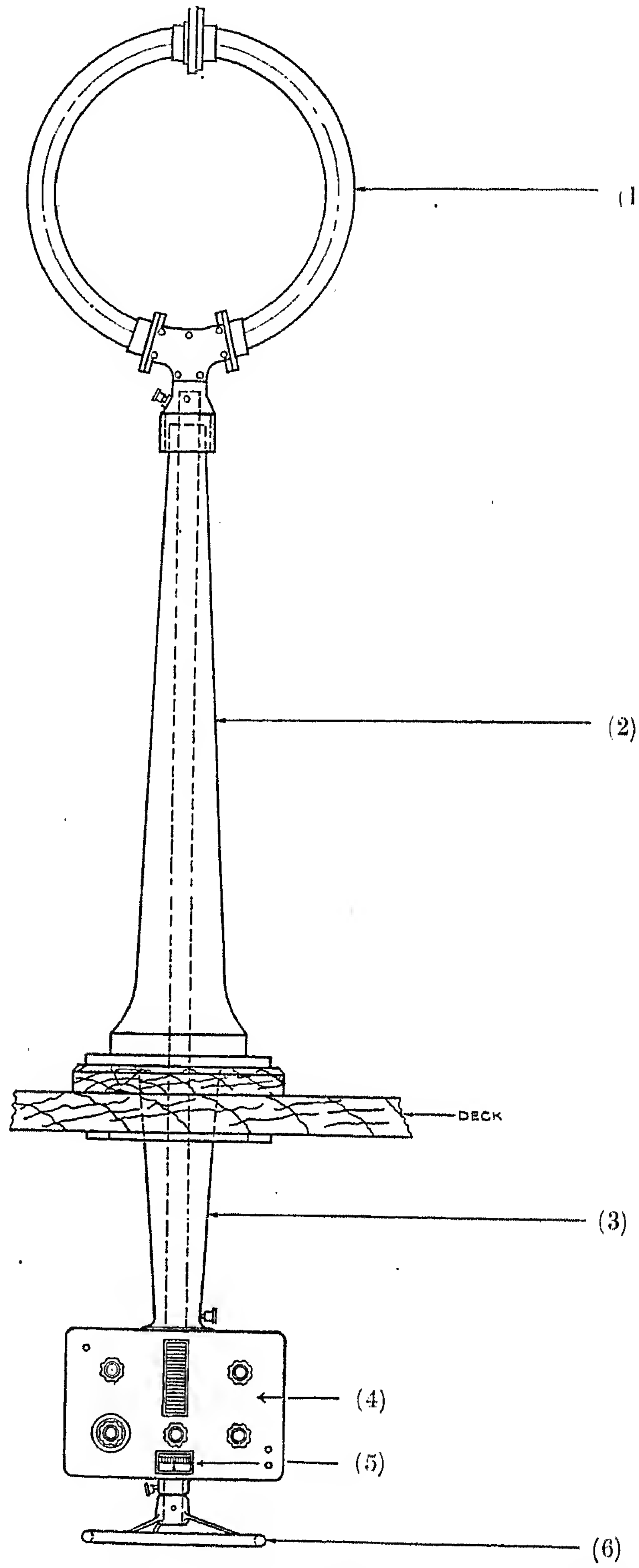


Fig. 2.—Simple type of rotating-loop direction-finder.
(1) Loop.
(2) Deck pedestal.
(3) Receiver suspension.
(4) Receiver.
(5) Direction scale.
(6) Handwheel.

The loop winding consists of standard rubber-covered wire supported inside an earthed copper shielding 27 inches in diameter on a system of insulating spreaders to obtain minimum capacitance and a symmetrical wind-

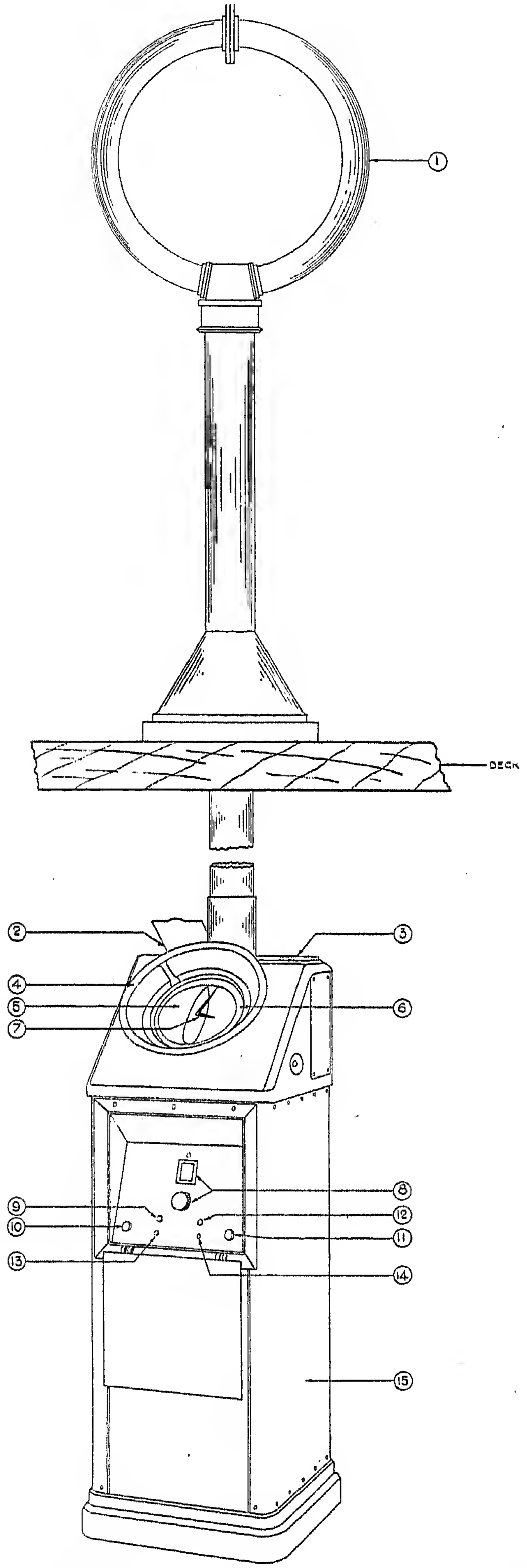


Fig 3.—Rotating-loop direction-finder, R.M.S. "Queen Mary."

(1) Loop.
(2) Loud-speaker.
(3) Headphone pocket.
(4) Handwheel.
(5) Inner stationary scale.
(6) Outer gyro scale.
(7) Direction and sense pointer.
(8) Tuning control.
(9) Sense control.
(10) Balance control.
(11) Volume control.
(12) C.W.–I.C.W. switch.
(13) On-off switch.
(14) Telephone jack.
(15) Binnacle containing batteries and charging board.

ing. The leads are brought down the loop driving shaft to the collectors, and the centre tap is also brought to the receiver so that it may be disconnected for a leakage check when required. The centre of gravity of the loop assembly has been placed at a low point so that in case of excessive vibration of the vessel the assembly will not tend to oscillate like a pendulum. The complete assembly is designed to withstand a wind pressure well in excess of hurricane force.

The loop is rotated through accurately-cut gearing by means of the handwheel which is mounted upon the sloping top of the binnacle. A friction brake is provided above the indicator housing for locking the loop in place when desired. The binnacle, which is constructed of corrosion-proof aluminium alloy, serves as a housing for the loop handwheel with its gearing, compensator and indicator mechanism, receiver, batteries, etc. The interior of the binnacle is kept dry by means of a heater located in the lower part. A loud-speaker is mounted inside the top of the binnacle and is provided with a hinged cover which serves as a reflector to direct the sound toward the operator. A compartment with hinged cover is also provided at the top of the binnacle to house the headphones when not in use.

The indicator is a mechanically-compensated completely automatic type in which the pointer showing the loop bearing leads or lags behind the actual loop position to compensate for quadrantal error, i.e. the deviation from actual bearing due to distortion of wavefront by the ship's structure. It makes use of a stationary cam and movable roller with associated linkage to shift the pointer to one side or the other according to the compensation required, up to a limit of $\pm$ 22°. The indicator face carries a large full-vision dial showing the outline of a ship at its centre, to aid the navigator in visualizing the relative bearings obtained. A movable outer scale, divided into 360 degrees, is provided for obtaining true bearing and is operated by a Sperry repeater motor mounted inside the binnacle and in step with the master gyro-compass. Relative bearings (i.e. bearings relative to the ship's head) may be taken from the stationary inner scale. The long end of the pointer indicates the bearings on the scale, while the short end of the pointer is used in conjunction with the "sense" button on the receiver to remove the 180° ambiguity from the direction-pointer readings.

The receiver is a single-dial-control, tuned radio-frequency unit containing four H.F. stages, three of them tuned by four resonant circuits, including the loop, and one untuned stage, followed by a detector with separate beating oscillator, and two stages of low-frequency amplification. Indirectly-heated valves are used throughout. The tuning range is 250 to 550 kc. (1 200–545 m.).

(1.82). Radio Beacons.—An important factor in the development of the direction-finder as a navigating instrument has undoubtedly been the interest displayed by maritime countries in the organization of a system of radio beacons.

These radio beacons come under the jurisdiction of the lighthouse authorities and, in order to avoid mutual interference, are as far as possible arranged in groups. By international agreement the band of radio frequencies allocated for radio-beacon services in the European area

is 290 to 320 kc. (1 034–938 m.), and in the organization each group is allocated special radio and modulation frequencies, and fixed times of transmission, accurately regulated by clock control. Each beacon has also a simple and distinctive identification signal.

A typical radio-beacon group in British waters is composed of three radio beacons, each transmitting for a period of 2 minutes, the transmissions being so arranged that only one of the three is in operation at any moment.

Beacons of another type intended primarily for aircraft and for use by ships not fitted with direction-finders have been erected at Orfordness, Tangmere, and Rangoon. This type of beacon, which has been fully described in the *Journal* (1931, vol. 69, p. 523), utilizes directional transmission, the direction being slowly rotated through 360° at a definite rate. A special signal is transmitted when the beam is pointing north and south, and bearings are obtained from such a beacon by means of a stop-watch used in conjunction with an ordinary receiver.

On certain lighthouses and light-vessels the radio-beacon system is used not only for direction-finding but also for position-finding. In such cases the radio transmission is arranged to synchronize at a definite moment with either a submarine sound signal or an air fog-signal; the first system is that usually employed, although there are several examples of the second on the coasts of the United States, as well as a radio "talking beacon" at Little Cumbrae on the Firth of Clyde. The method of operation is essentially the same in both cases, the distance of a ship from the beacon being obtained by noting the time which has elapsed between the receipt of the radio signal and that of the sound signal synchronized with it. This time in seconds, multiplied by 0·8 in the case of submarine signals, and by 0·18 in the case of air fog-signals, gives the distance of the ship from the beacon in nautical miles.

The Little Cumbrae talking beacon consists of an air fog-signal working in conjunction with a small radio-telephone transmitter modulated from a gramophone record. The two transmissions are synchronized in such a way that the observer on board the ship hears his distance from the beacon spoken in cables and miles on the radio, at the instant he hears the third blast of the fog signal on the air.

In 1936 there were about 300 radio beacons altogether, concentrated for the most part in the North of Europe (125 beacons) and on the east and west coasts of North America (35 and 67 beacons respectively).

(2) NORMAL SHIP EQUIPMENTS

(2.1). Special Design Considerations.

From the mechanical aspect the design of marine equipment in general is governed to more than the usual extent by space considerations. Space is unavoidably an expensive asset on any ship, and it is necessary to control not merely the actual volume of the apparatus but also its shape and mounting so as to obtain the maximum utilization of whatever space may be available, having regard not only to bulk but also to convenience of location for normal operation, and—what is equally important—to ease of access for maintenance purposes. In the case of ships which after some years' running require the installation of additional equipment to handle new communication services, the problem of space utilization may be serious, as shipbuilders not unnaturally make no allowance for such extensions. Another important factor which bears on the design is vibration. A certain amount of vibration is inevitable in all cases, and in some ships at particular speeds or in rough weather vibration may be very marked indeed. Due allowance must be made for this in the method of fixing or mounting the apparatus, as continued vibration may ultimately result in the development of faults in the equipment, or may even interfere directly with its operation, particularly where short-wave working is concerned.

Quite apart from the mechanical requirements implied in the foregoing, it is also necessary to remember that marine equipments are continually subject to a salt-laden atmosphere, and also to large temperature-changes according to the time of year and the ship's route. It is therefore necessary to pay special attention to the choice of materials and finishes.

While the mechanical factors mentioned above apply to all classes of ships, the electrical aspect varies a good deal according to the class of ship and to the services to be maintained. One difficulty, the provision of an efficient aerial system, is common to all classes. Contrary to what might be thought, the efficiency of the average ship's aerial is low, of the order of 10 per cent, which contrasts severely with the figure of 60 to 80 per cent which is common with aerials erected for broadcasting stations. Apart altogether from the consideration that, unlike a broadcasting station, a ship may have to use the same aerial over quite a wide band of wavelengths, a ship cannot be considered as a good aerial site. Limitations as to height and length, combined with reaction from nearby metal funnels, metal masts, and wire stays and rigging, which may or may not be efficiently earthed, all work together to impair the radiation properties of the aerial. These deficiencies are to some extent compensated by the ease with which a relatively good "earth" can be obtained through the ship's hull. Good ship communication on medium wavelengths, despite the relatively poor aerial, is, however, undoubtedly mainly due to the low attenuation involved in the over-water propagation path around the ship.

When it becomes necessary, as in the case of a large liner, to install within the limits of beam and fore-and-aft dimensions a number of aerials which may be in use simultaneously, it is a difficult matter to overcome the effects of unwanted coupling between the aerials themselves and between the aerials and stays, etc. Such couplings affect not only the efficiency but also the radiation polar diagram, the latter being a serious matter on short-wave circuits. They also introduce considerable difficulty in duplex working, a feature of increasing importance in the largest passenger liners (and also in naval vessels), rendering necessary the provision in the receiving systems of special "pre-selecting" circuits using components capable of withstanding considerable voltage.

Since it is customary to run radio transmitters directly from the ship's mains, it is of importance that the regulation of the latter should be good, particularly where valve transmitters are employed. This require-

ment does not give rise to any difficulty in the larger class of passenger ships, but, where other vessels are concerned, experience shows that the radio designer must make some provision for considerable voltage variations in the mains.

A feature which applies to marine radio with special force is the necessity for facilitating maintenance work under service conditions. Accidents will happen even in the best constructed equipments, and it is essential that the designs be so laid out that an operator, working in very restricted space, with perhaps the additional handicap of violent motion of the ship in a rough sea, can obtain reasonable access to all components and wiring points. It may well be said that in comparatively large units such as transmitters and the more elaborate receivers, this requirement dominates the detail of the whole mechanical design.

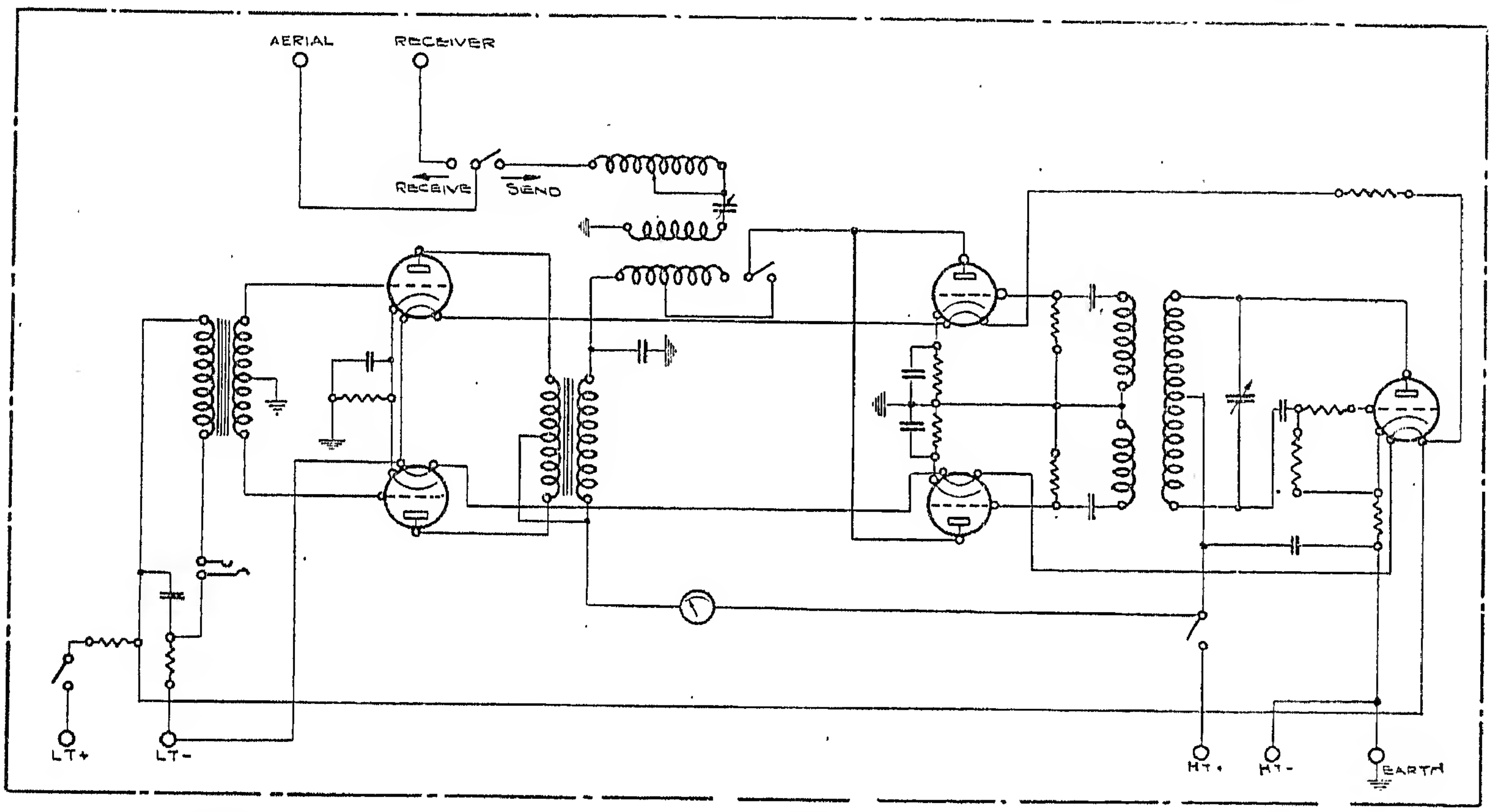


Fig. 4.—Circuit diagram of radiotelephone transmitters for trawlers and coastal vessels.

Recent developments in marine radio design have been characterized by the increased attention paid to the points just mentioned as compared with the practice of the previous decade. It is, of course, true that troubles such as vibration, bad mains regulation, and so on, are by no means novel, but they were of little importance in the days when traffic was handled at relatively short ranges by spark transmitters and low-sensitivity receivers. It is only now, when valve transmitters, high-sensitivity receivers, and long-distance working, are the order of the day, that it has become necessary to take definite cognizance of these site factors which militate so seriously against both operation and maintenance.

(2.2). Transmitters.

As mentioned earlier in this paper, the last few years have seen a rapid increase in the number of "voluntarily" equipped ships, particularly trawlers. For this class of vessel the fundamental requirement is radiotelephony on a simplex basis, "skipper-operated." The circuit diagram of a typical transmitter for this service is shown in Fig. 4. Master-oscillator control is used in order to simplify setting to any particular wavelength, and is followed by a frequency-doubling stage deeply anode-modulated by a push-pull L.F. amplifier. It is at once evident that in this equipment telephony is the normal method of operation and not merely the auxiliary feature which it was considered some years ago, and which was often thought sufficiently well provided for by low-amplitude grid modulation. This particular equipment covers a waveband of 120–220 m. and has an output power of the order of 25 to 50 watts. Its operation is therefore confined to the special telephony band provided for trawlers and other coasting vessels. If it is desired that the vessel should in addition be able to communicate by telegraph on the medium-wave band another equipment of rather more power (up to about 75 watts output) is employed. Deep modulation remains a definite characteristic in all cases.

Turning to vessels of the "compulsorily equipped" class, all of which carry trained operators, in cases where little traffic is handled, e.g. small cargo vessels, it is usual to provide relatively simple valve telegraph equipments operating in the medium waveband of 600 m. to 800 m. and having a power output of the order of 150 watts. When, however, we come to the larger class of cargo vessel and to small liners, requiring more than the legal minimum of communication facilities, the outstanding feature of recent years has been the adoption of short-wave working for long-distance traffic. This involves the provision of equipment of a relatively high grade. Master-oscillator control becomes essential, with the optional addition of some kind of stabilizing device such as a quartz crystal. A common arrangement in this class of vessel is the use of a composite equipment of two

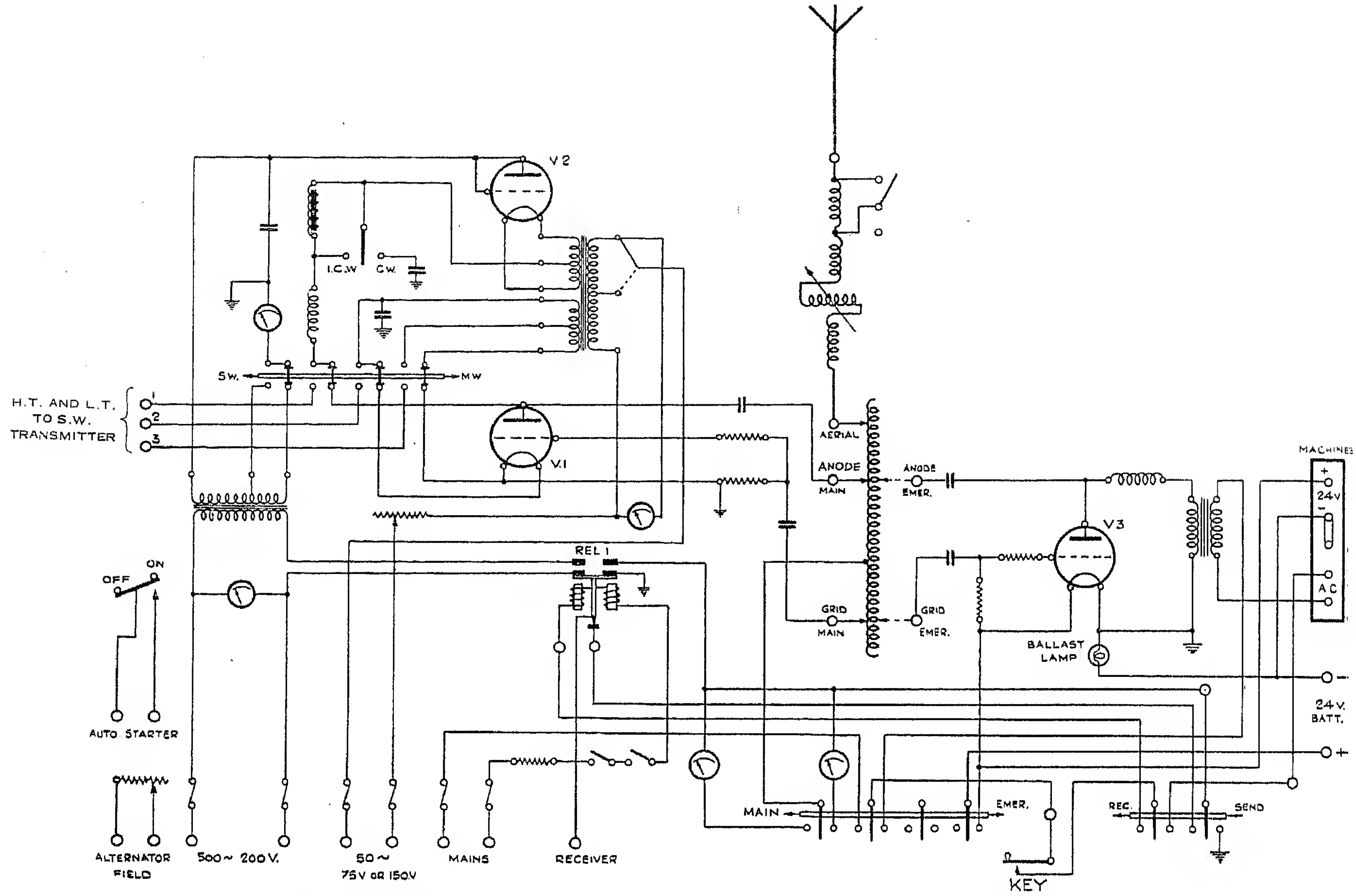


Fig. 5A.—Circuit diagram of medium-wave unit of composit e transmitter for large cargo vessels.

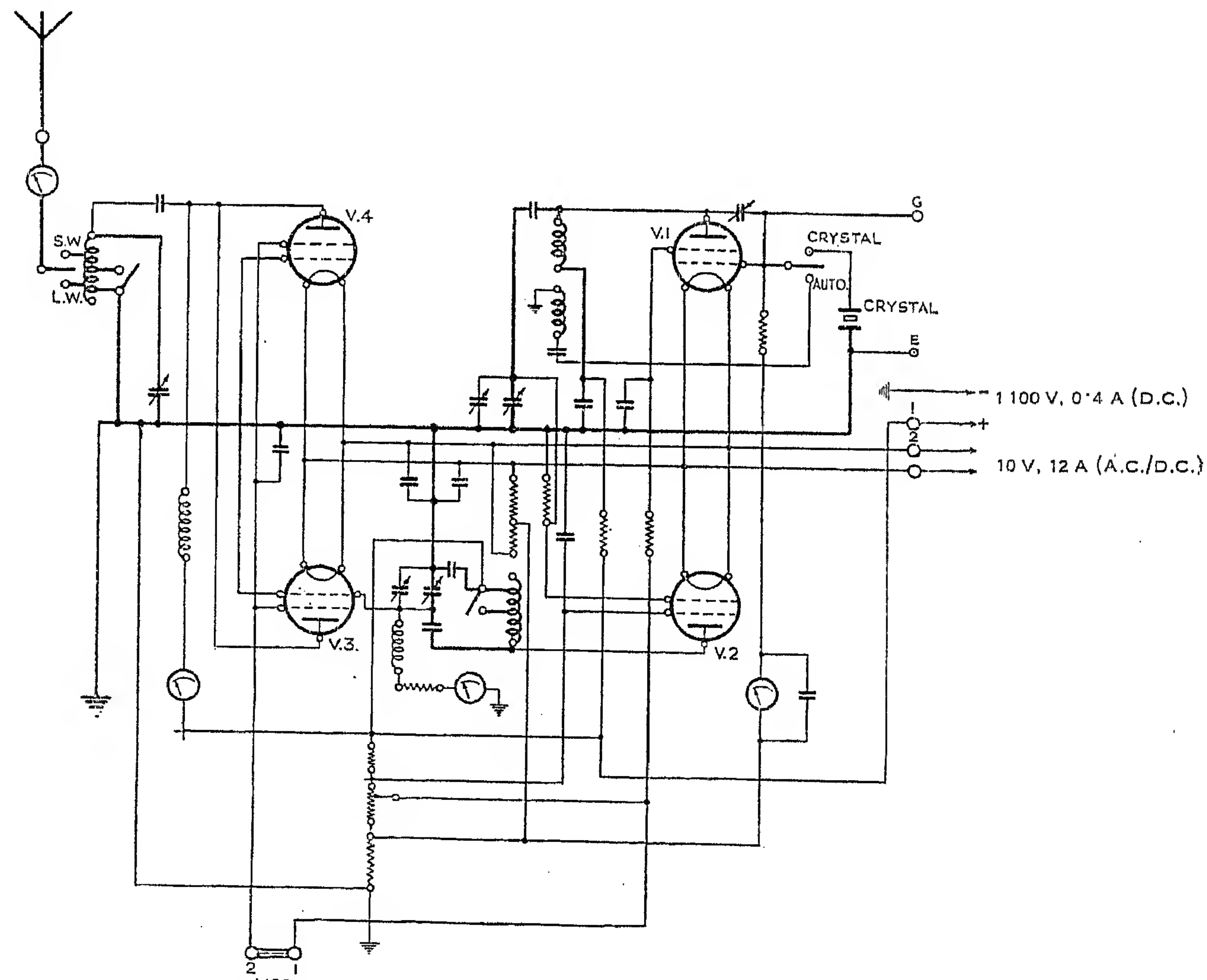


Fig. 5B.—Circuit diagram of short-wave unit of composite transmitter for large cargo vessels.

units covering separately the medium and short wavebands. In one example of this type of equipment the medium-wave unit, shown in Fig. 5A, includes the main power supply circuits for both units, and in addition it incorporates the emergency transmitter of lower power. It may be operated on either C.W., using a smoothed rectified a.c. H.T. supply to the anode of the main transmitting valve, or on M.C.W., in which case the H.T. supply is rectified but not smoothed. The output is approximately 500 watts. The keying system controls through a relay the supply to the primary of the H.T. transformer and also switches the aerial to the receiver when the key is "up," thus permitting "break-in" working. The short-wave unit, shown in Fig. 5B, is master-oscillator driven, crystal-controlled on two spot wavelengths, followed by two stages of amplification. All valves are of the screen-grid pattern. While the output of this short-wave unit is comparatively small—approximately 100 watts—it is sufficient under ordinary conditions to give world-wide telegraph communication for several hours per day. A simplified version of this type of equipment, in which the facilities for short-wave and C.W. working are omitted, is occasionally installed by ship-owners whose traffic requirements do not seem to justify fitting anything more elaborate.

For the intermediate and larger class of passenger vessel, in which the handling of public correspondence becomes of greater importance, a more flexible type of transmitter than the above is generally used. One example of such a transmitter, providing a wide range of service, covers the following wavebands:—

(*a*) 15 m. to 60 m.; output 200 watts.
(*b*) 550 m. to 800 m.; output 500 watts.
(*c*) 1 875 m. to 2 725 m.; output 500 watts.

In all the bands master-oscillator drive is used, usually without crystal control or other special frequency-stabilizing device. Communication is possible on either C.W., M.C.W., or radiotelephony with anode modulation. The equipment is in effect two separate transmitters mounted, with a single power-supply unit, in a common framework. Its essential characteristic may be described as flexibility in wavelength combined with average good all-round efficiency, rather than specialization for any particular requirement. Power supply is taken from a motor-generator set. In the class of vessel which requires this type of gear the regulation of the mains is usually sufficiently good for any variation to be taken up by the motor-generator set alone, and the use of ballast lamps in filament circuits, etc., is unnecessary.

(2.3). Receivers.

In spite of the great development in the use of the valve for reception purposes during and after the War of 1914–18, crystal receivers were retained as the normal equipment in a very large number of ships until about 1930, and the Washington Convention did not find it possible to make valve reception a compulsory requirement until the 1st January, 1932. The first applications of the valve to mercantile marine reception took the form of auxiliary valve units operated in conjunction with the standard crystal tuner, the crystal being switched out of

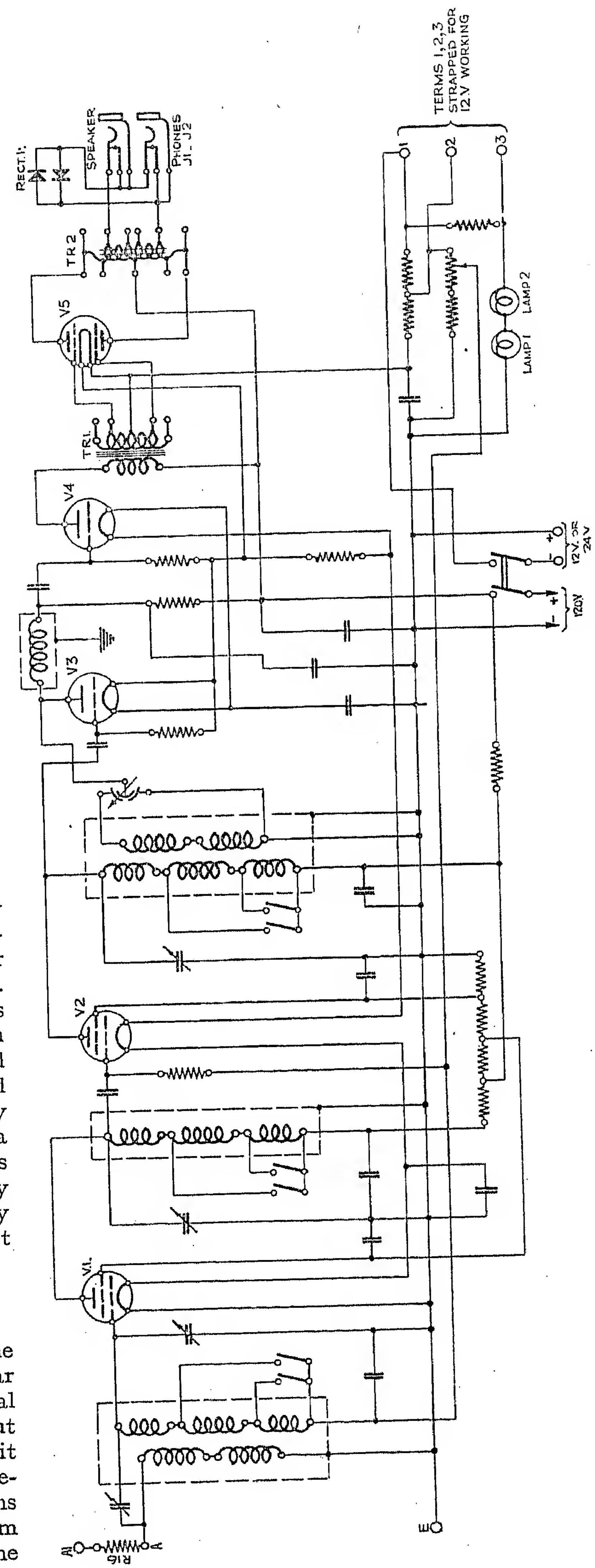


Fig. 6.—Circuit diagram of receiver for trawlers and coasting vessels.

circuit. To-day, however, the valve receiver as such is in universal use at sea, although crystal reception must still be available (under the Safety of Life at Sea regulations) for emergency purposes in the event of failure of all valves or batteries.

While the development of receivers for marine use has of course been to some extent influenced by the progress of design in the broadcast receiver field, there are nevertheless sufficient differences in the performance requirements to give the marine receiver definite individuality. One of these differences is the demand for very wide wave coverage associated with marine work.

In the case of the "voluntarily equipped" trawler and coasting class of vessel, while the transmitter may cover a waveband of only 110 m. to 200 m. (1 500 kc. to 2 730 kc.), the receiver demanded has to cover a band of 110 m. to 2 000 m. (150 kc. to 2 730 kc.), in order to permit reception of broadcast weather bulletins, etc. The circuit diagram of a receiver designed for this class of vessel is given in Fig. 6. This is a "straight" ganged-circuit 5-valve receiver, in which the waveband is covered in three sections selected by switch. Where strong interference from a nearby transmitter is to be expected the aperiodic receiving aerial may be connected to terminal A1, the resistance R16 serving to prevent swamping. Both loud-speaker and headphone reception is provided, the headphones being normally shunted by a small full-wave rectifier which acts as a signal and atmospheric limiter.

An example of a simple receiver for use in compulsorily equipped ships of the cargo class is the 3-valve set whose circuit diagram is shown in Fig. 7. This has a wavelength range of 13·5 m. to 20 000 m. spread over 8 switch-selected bands, with single-dial 2-circuit tuning throughout the whole range. A plug-in crystal detector unit, connected across the input tuned circuit, is provided for emergency working.

While such a receiver is sufficient in many cases, it is obvious both from the circuit and from the extended wave-range that its sensitivity on the shorter wavelengths cannot be very high, and where short-wave long-range working is a regular part of the ship's communication it is usual to fit an additional separate receiver designed to cover with high efficiency only the limited band of, say, 15 m. to 60 m.

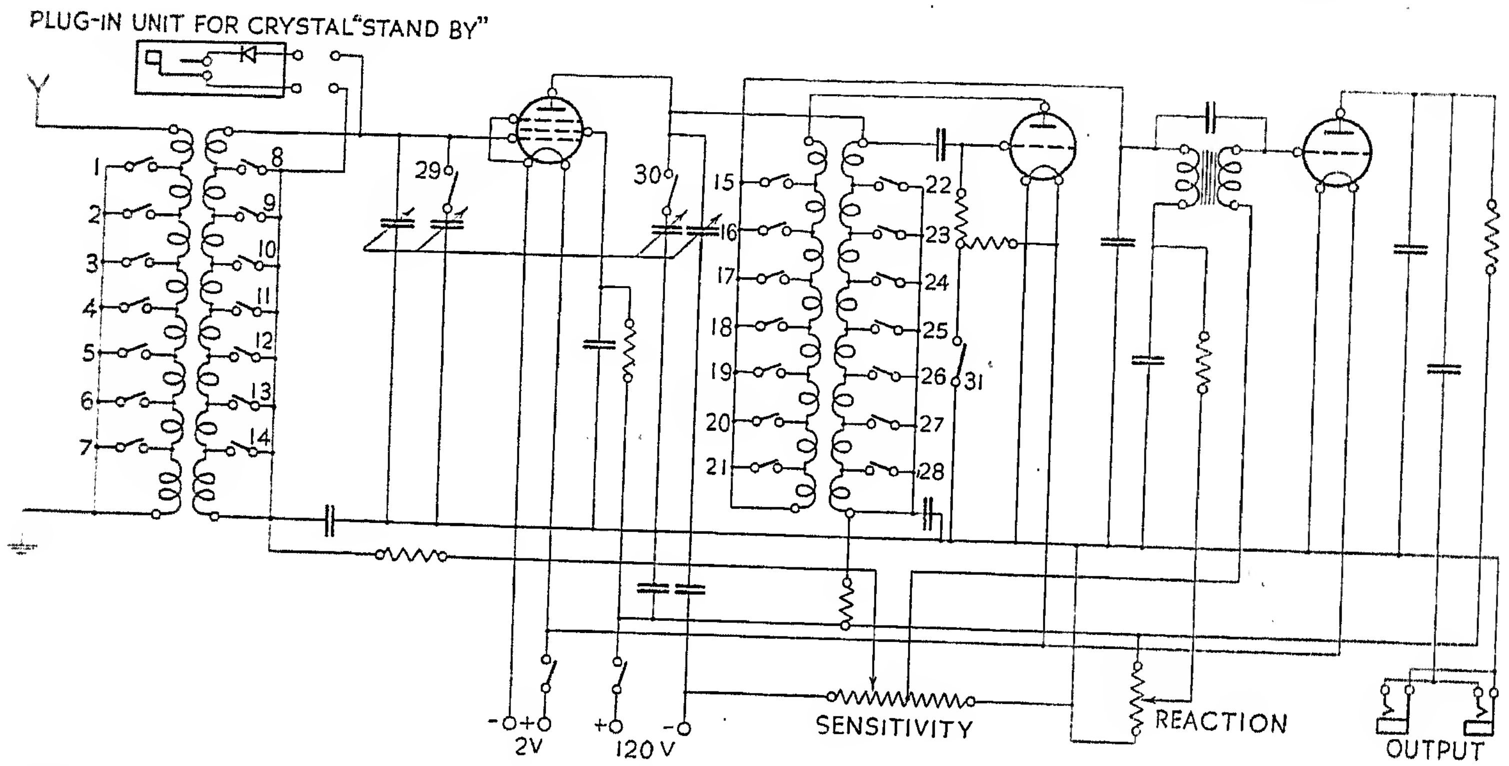


Fig. 7.—Circuit diagram of general-service receiver for compulsorily-equipped ships (waveband 13·5-20 000 m.).

(3) EXPRESS STEAMER EQUIPMENT

(3.1). Preliminary Note.

While the types of equipment discussed briefly in the preceding Section are capable of meeting the more or less routine requirements prevailing in the majority of vessels, they are unsuited to the efficient handling of the radio services required on vessels of the "express steamer" class, of which R.M.S. "Queen Mary" is the latest example. Such vessels are, however, relatively few in number, and orders for their equipment are usually sufficiently spaced in time to make it both economical and desirable to consider each case separately as it arises, in order to take advantage of the latest technical developments. It follows that equipment for the "express steamer" is by no means standardized, and, although the basic problems remain much the same in all cases, the manner in which they have been attacked may vary from one ship to another according to the date of installation, etc. In this Section consideration has been almost entirely restricted to the equipment actually installed in R.M.S. "Queen Mary," as illustrative of the most recent technique in this somewhat specialized field of application of marine radio.

(3.2). Determination of Principal Requirements.

The two primary considerations in deciding on the equipment to be fitted in a large passenger vessel are, firstly, navigation and safety of the ship, and secondly, the public radio-telegraph and -telephone service. While

the first is still the most important function of the radio station on board, it presents no real problem and can be amply catered for by quite orthodox and standardized arrangements.

The second consideration, that of the public radio service, becomes of greater importance as the size of the ship and the passenger accommodation increases, and, in the largest transatlantic vessels, is the real deciding factor as to the equipment which is to be supplied to the ship. The volume of radio traffic handled is considerable, and it is of great importance that it be cleared with the minimum of delay.

As a preliminary to the planning of the "Queen Mary" station, a study was made of the traffic returns from 1926 onwards in the two largest Cunard vessels, "Aquitania" and "Berengaria." This yielded interesting and useful data, showing that the expenditure per passenger on messages was practically a constant figure over the 8-year period considered, irrespective of the number of passengers carried. It also revealed well-defined daily peak traffic-load periods, the most important of these being around the closing hours of business houses on both sides of the Atlantic, and therefore the times when messages must be cleared with the greatest despatch. Further peak-load periods may occur at irregular intervals, the worst type of such abnormal load taking place when a ship just misses the tide on arrival day and is held up for a number of hours; under such conditions, large numbers of passengers wish to advise those who are meeting them, and the traffic load rises abnormally for several hours.

Taking into account the foregoing considerations, an estimate was made of the heaviest radio traffic load the "Queen Mary" would be called upon to handle. With this as a basis, and with the need of providing a "no-delay" service, the conclusion was reached that multiplex working would be essential in order to cater for the peak-load conditions as well as to enable the ship to keep in constant simultaneous touch with both sides of the Atlantic and with other ships. It was calculated that four transmitting channels and four receiving channels would be required—two on the short waveband for simultaneous eastbound and westbound communication, one on the medium waveband and one on the long waveband. Automatic transmission and reception at moderately high speeds on at least two or three channels was also considered desirable.

The above remarks apply primarily to telegraph traffic. In order to provide for the radiotelephone service a further analysis of the voyage returns of the express steamers was made and the conclusion was reached that simultaneous communication with both London and New York would certainly be required at times and that the most efficient and economical arrangement would be to incorporate radiotelephony in both short-wave transmitters rather than to install separate equipment. Experience in the "Berengaria" and "Aquitania" indicated that the incorporation of telephony in this manner would not impede the handling of traffic as a whole.

Having determined the number of operating channels required, the next question was how to provide them in the most efficient way. The chief problem was that of multiplex working, which, in the confined space of a ship, presented no little difficulty. Not only was operation on four different wavebands required without mutual interference, but duplex working in each of these wavebands was also aimed at, up to the limits of practical working range of the transmitters.

A certain amount of experience in this direction had previously been gained in the "Aquitania" and "Berengaria" when multiplex working on two wavebands was attempted in 1929–30. Only a limited success was then achieved, owing to the quality of the long-wave transmitters employed (simple auto-oscillators rich in harmonics) and to the unsuitable nature of the receiving valves then available. The results were, however, encouraging, duplexing on the 2 000-metre band being obtained at ranges up to 500–1 000 miles, and on short waves (using crystal-controlled transmitters and commercial-type superheterodyne receivers) at all distances, subject to harmonic interference from the long-wave transmitter.

Based upon the experience gained in these two ships, it was clear that the primary requirements for efficient multiplexing were, firstly, separation of the transmitters and receivers with their associated aerials by as large a distance as possible; secondly, the provision of receivers having considerable selectivity and ability to withstand high voltages picked up by their aerials from the local transmitters; thirdly, the provision of transmitters as free as possible from harmonic radiation. A number of other relatively minor difficulties, such as interference between adjacent operating positions due to key-clicks, and receiver inter-action, "stay noises," etc., also had to be overcome.

Some separation of the transmitters and receivers was not a difficult matter to achieve in so large a ship, and suitable sites for the transmitting and receiving stations 400 ft. apart were obtained.

One of the most important features in the rapid handling of traffic is the ability to change wavelength quickly. This especially applies to the short wavebands when combined telegraph/telephone equipments are used, since special wavelengths are allocated to each of these services, and in order not to delay either service it is necessary to be able to change from the one to the other very quickly. Consequently it was decided to provide complete remote control not only for keying and power but also for rapid selection of any one of a number of preselected wavelengths.

The power and frequency ranges of the transmitters remained to be decided. For the medium and long wavebands the factor limiting good communication is as a rule the signal/noise ratio. Since these frequency bands are part of the main communications of the ship, and have to carry the whole of the telegraph load at times when the short-wave channels are both occupied for telephony, or when short-wave communication is poor, it was considered necessary to provide the highest power practicable. A power of 3 kW in the aerial circuit was finally decided upon, the limiting factors being space available for installation and the maximum voltage permissible on the aerials. The transmitting aerial constants were of considerable importance in this connection, since any brush discharge would give rise to damped waves which would shock-excite the receiving aerials and prohibit multiplexing.

For short-wave communication, conditions are somewhat different. While the limiting factor, especially for telephony, is again the signal/noise ratio, experience has shown that the borderline cases are not the general rule; that is to say, for any particular frequency, conditions are generally either good or bad with the average powers in use. When conditions become bad it is better to change frequency rather than to increase power. Experience gained in the "Aquitania" and "Berengaria" showed that, with the aerial powers in use in those ships, well over 90 per cent of radiophone calls could be satisfactorily completed. Increasing the power by 10 times, giving an increase in signal/noise ratio of some 10 db., would have added about another 5 per cent to the total—a desirable feature, but scarcely worth the corresponding disadvantages of extra space and power supply required, greater difficulty of control, higher "stay noises," and higher initial and maintenance costs. On the other hand, it was estimated that by providing suitable directional aerials an effective increase in signal/noise ratio of between 5 and 10 db. could be anticipated, equivalent to an increase in power of some 3 to 10 times. This was confirmed by preliminary experiments carried out in the "Berengaria," when even greater increases in signal/noise ratio were reported. It was consequently decided to use an aerial power of approximately 400 watts, and to concentrate on providing the most efficient aerial system possible.

A similar argument holds good for the receiving aerials, and experiments were carried out with different types of these in order to obtain the maximum signal/noise ratio. In this case, besides providing as much directivity as possible, interference from ship's machinery had to be avoided by suitably arranging the planes of the aerials, providing shielded feeders, etc.

Finally, the question of power supply for the stations remained to be settled, and it was eventually decided to use one common source of supply for the whole station, in the form of 3-phase alternating current.

The various technical requirements outlined above called for apparatus somewhat outside of the normal standardized equipments, particularly as regards the remote control of wavelength, the power output of the transmitters, and selectivity of the receivers. For this reason, practically all the apparatus on board was either specially designed (or modified from existing standard designs) as described below.

(3.3). Short-Wave Transmitter.

In the case of the short-wave transmitter the factors chiefly influencing the design are the provision of (*a*) very stable carrier; (*b*) quick change from one spot wave to another; (*c*) moderate output power of approximately 400 watts. The stable-carrier requirement is met by the provision of a separate quartz crystal for each wavelength, followed by five amplifying stages in order to reach the required output level. This involves a number of tuned circuits, each requiring adjustment by tappings or otherwise for each spot wavelength. The use of tappings on short wavelengths is practicable only to a limited degree, and accordingly the wave-change principle embodied in this transmitter is the provision of entirely separate tuning units at each stage for each of the 10 spot wavelengths, the valves being connected to the appropriate tuning units through switches operated simultaneously under the control of a telephone dial. Fig. 8 shows a simplified circuit diagram of the radio-frequency stages with all the tuning units for one wavelength, D1, D2, etc., being the switches connecting the permanent valve circuits to the tuning units. The latter are of plug-in pattern, and are available for a waveband of 16·6–150 m. (frequency 2–18·1 megacycles).

The transmitter consists of two cabinets, each of dimensions approximately 24 in. wide, 30 in. deep and 83 in. high, mounted side by side. One cabinet contains the radio-frequency valves and circuits, while the second contains the audio-frequency amplifiers together with the rectifiers and other apparatus. Both cabinets are of the enclosed type with access to apparatus through doors. A ventilating fan is included in the radio-frequency cabinet. The entire equipment is designed to operate from a 3-phase 50-cycle 220-volt source, and has a power consumption of approximately 3·5 kW at full load.

As can be seen from Fig. 9, the radio-frequency cabinet includes a number of sub-units of chassis construction. Starting from the bottom, these are: oscillator stage, first buffer stage, second buffer stage, modulated amplifier stage, output-valve compartment, and output stage. Each chassis mounts a total of 10 plug-in tuning units, while the bottom chassis in addition mounts up to 10 quartz crystals. Adjustment of any of the tuning units can be performed, while the equipment is in operation, by means of a tool inserted through an aperture in the grounded front cover-plate of the chassis. All the chassis are quickly removable for examination of components, and are automatically disconnected at all terminals as they are withdrawn from the cabinet.

Both the first and the second buffer stages may be used either as straight amplifiers or as frequency doublers, according to the relation between the crystal frequency and the required frequency. For telephony or M.C.W. the modulating voltage is applied in series with the high-tension supply to the penultimate valve, and modulates both plate and screen-grid voltages. Keying is effected at the plate of the oscillator, which is earthed through a key-controlled relay system during the spacing periods. When the transmitter forms part of a radiotelephone link circuit the carrier is, by means of the terminating equipment described later, automatically switched on while the ship subscriber is speaking. In this case the actual switching removes the earth from the plate of the oscillator, as during keying, but the train of relays involved is adjusted so as to provide a short "hangover" period of 150 milliseconds to prevent the transmitter being switched off in the intervals between words.

The wave-change system employed is relatively simple. At the back of the transmitter is a row of 10 vertical rods, one for each wavelength; at the foot of the transmitter is a horizontal shaft equipped with 10 cams which are normally free on the shaft. On dialling the single digit number allocated to the wavelength or "channel," the appropriate cam is locked to the horizontal shaft which then rotates the cam, raising the corresponding vertical rod, the latter operating a number of bell cranks which close switches connecting into circuit the crystal

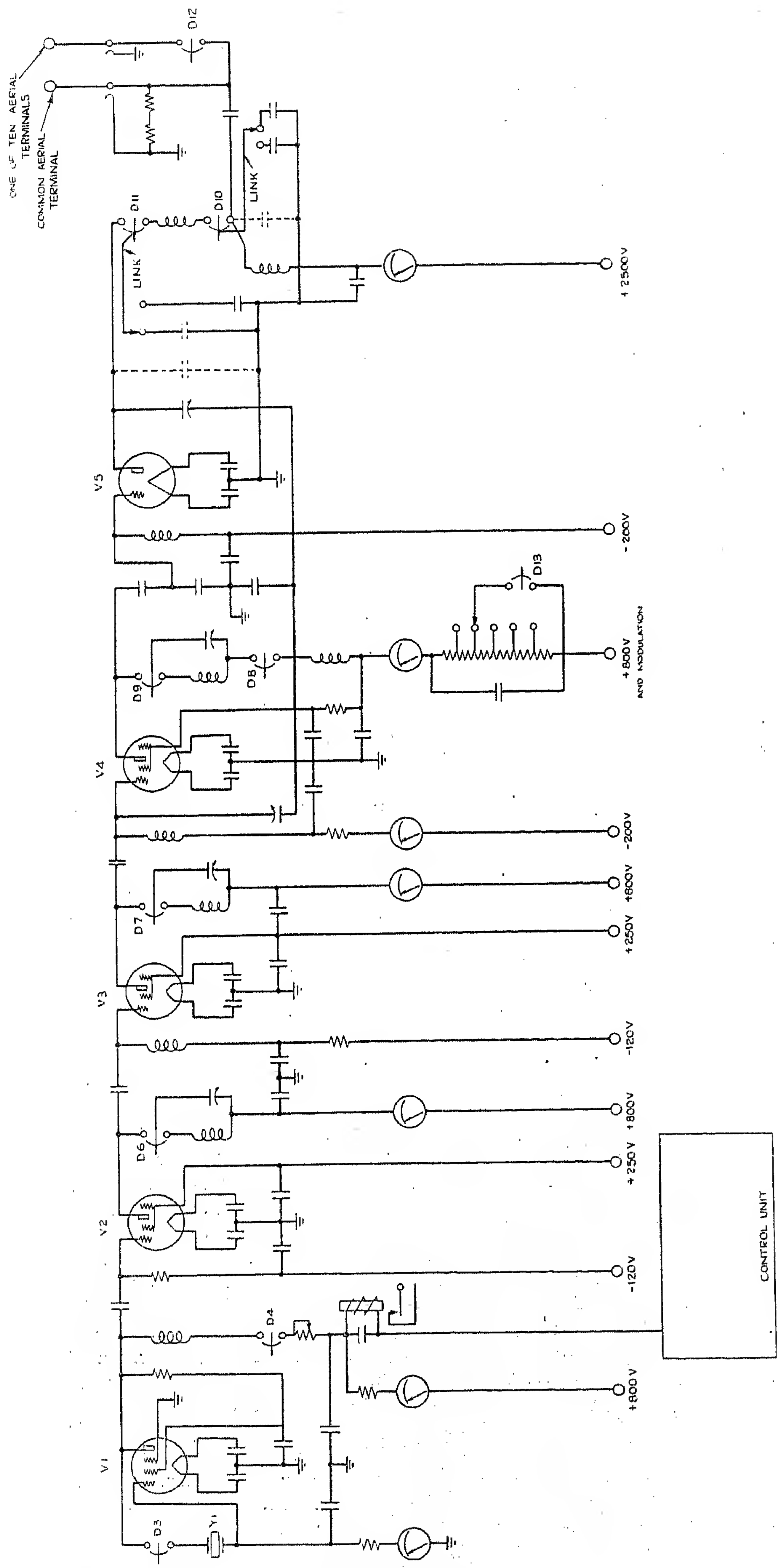


Fig. 8.—Simplified circuit diagram of short-wave transmitter, R.M.S. "Queen Mary."

and all the pre-set tuning units for the particular wavelength required. The time required to change wavelength depends almost wholly on the dialling operation, and varies from about 1 to 2 seconds according to the digit dialled. The wave-change system is interlocked with the protective system to remove the high-tension supplies during the circuit change.

The output circuits of the transmitter are designed to

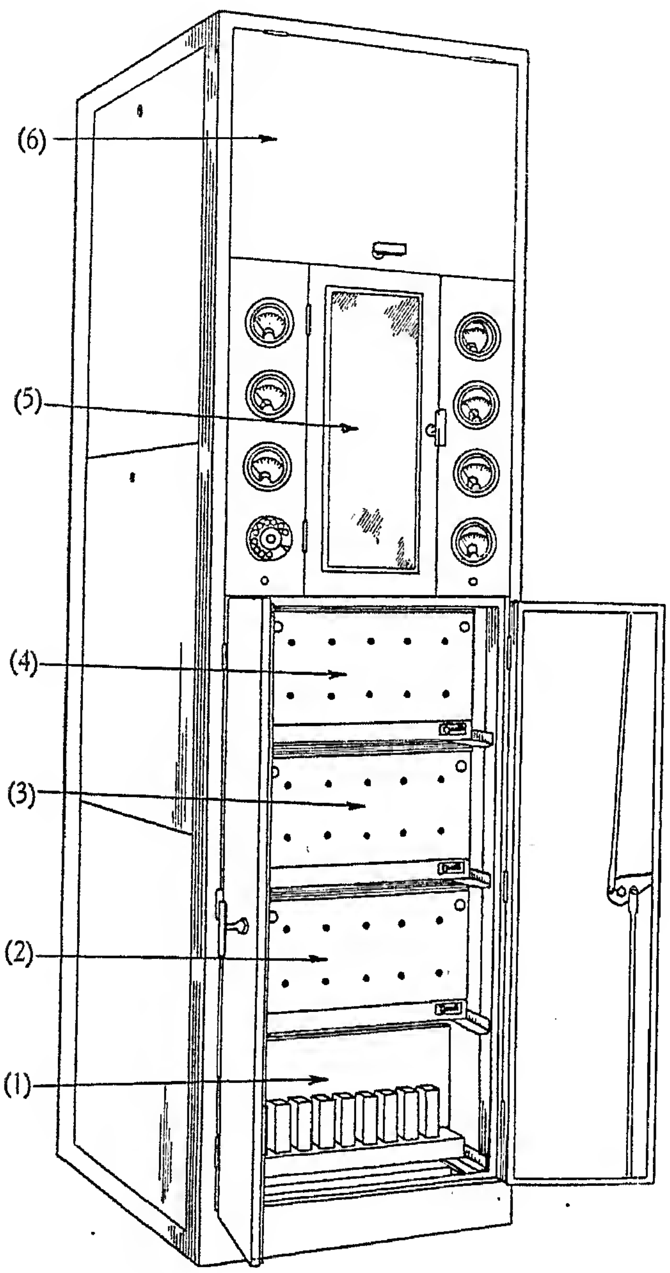


Fig. 9.—Radio-frequency cabinet of short-wave transmitter, R.M.S. "Queen Mary."

(1) Oxcillator stage.
(2) First buffer stage.
(3) Second buffer stage.
(4) Modulated amplifier stage.
(5) Output valve compartment.
(6) Output stage.

work into an impedance of 500 ohms; each output circuit is connected (through a switch forming part of the wave-change system) to its own aerial terminal and also to a common aerial terminal. Each wavelength may therefore have its own aerial directly connected to the transmitter, or alternatively the transmitter may always work into a common 500-ohm transmission line connected to one or more aerials through a separate tuning and coupling unit. In the latter case the coupling unit is equipped with the requisite number of plug-in type tuning circuits, together with a wavechange system of the same pattern as that used on the transmitter, and controlled simultaneously therewith. By means of this arrangement it is possible to use either open-wire or tubular feeders to the aerials, and to use the same aerial on more than one wavelength.

The power supply required for the transmitter circuits is derived from the second or rectifier cabinet. All filaments are heated by alternating current, while three hot-cathode mercury-vapour rectifiers—two of the 3-phase half-wave type and one single-phase full-wave—give the d.c. supplies for anodes and screen and control grid bias. The same cabinet contains a 2-stage audio-frequency amplifier to supply the modulating voltage; this amplifier will give full modulation with an input of 23 db. below reference level (5·9 milliwatts). The relay trains used for keying or voice-controlled carrier switching are also fitted in this cabinet, on a removable chassis mounted in the top section.

Remote control of the transmitter is centred on a special panel mounted on the same "operator's position" rack as one of the receivers in conjunction with which the transmitter is used. This remote panel provides for selection of any of the three possible types of communication—C.W. telegraphy, M.C.W. telegraphy, or radio-telephony. It is also equipped with a dial for wave selection, an 800-cycle oscillator to supply tone for M.C.W. modulation, a voltmeter which measures the speech-level supplied to the transmitter (and can be considered as a modulation indicator) and with controls for the depth of modulation, etc., as required for radio-telephone link working (dealt with in a following Section).

(3.4). Medium- and Long-Wave Transmitters.

Taking first the medium-wave transmitter, this covers a band of 585 m. to 822 m. with dial-controlled switching to any one of up to 10 spot wavelengths within this band, and aerial circuit power of 3 kW on C.W. or 3 kW plus 80 per cent modulation on M.C.W. Power input is from a 3-phase, 50-cycle source, with the transformers and any rectifiers required to furnish the various filament, anode, and grid, supplies, etc., included in the transmitter. The main H.T. rectifier uses hot-cathode mercury-vapour valves, but all other rectifiers are of the dry metal type.

Views of the general assembly are shown in Figs. 10 and 11. During operation the transmitter is completely enclosed, except for ventilating louvres, cooling being aided by a built-in blower system. Access to the interior is obtainable through doors which, when opened, operate gate switches to cut off the H.T. supply.

The basic circuit of the transmitter is shown in the simplified circuit diagram, Fig. 12. A single-valve self-biased master-oscillator drives a neutralized power-amplifier group of three parallel valves, the output of which is inductively coupled to the aerial through a tank circuit. Keying is performed through a high-speed polarized Creed relay which biases back the grid of the master-oscillator valve. Excellent signal wave-form is obtained up to key speeds of over 100 words per min. For M.C.W. operation the power amplifier is anode modulated by tone derived from a 700-cycle, 2-kW alternator. Provision is also made for low-power grid modulation of the power-amplifier stage, to give either telephony or M.C.W. of other than 700-cycle tone.

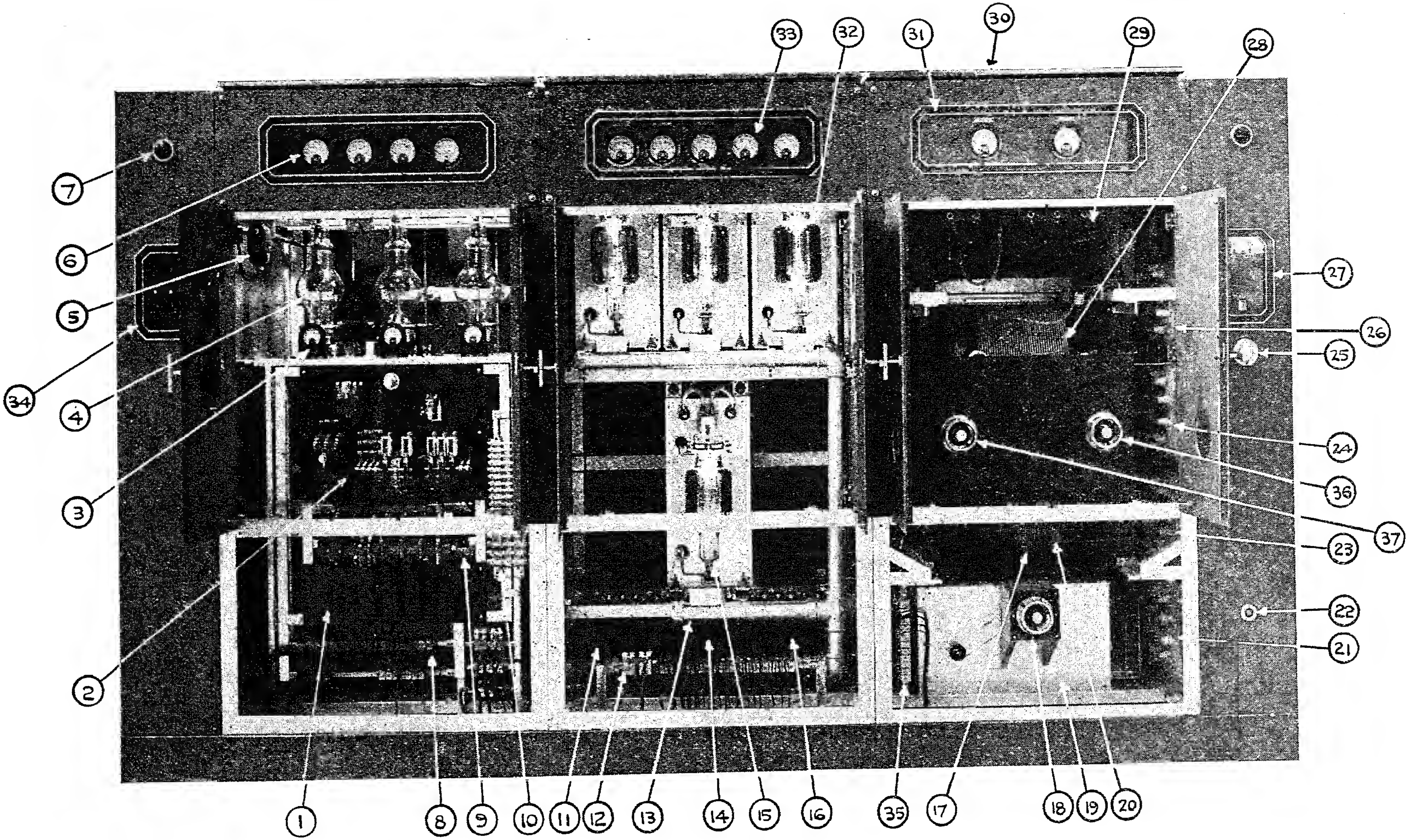


Fig. 10.—Front view of medium-wave transmitter, R.M.S. "Queen Mary" (cover panels removed).

(1) Rectifier main fuse panel.
(2) Rectifier power-control contactor panel.
(3) Rectifier valve-filament ammeters.
(4) Rectifier valves.
(5) Thermostatic air control.
(6) Rectifier meter panel containing anode ammeters and H.T. voltmeter.
(7) H.T. indicating lamp.
(8) Rectifier main terminal strip.
(9) Main contactor.
(10) Power-control panel strip connectors.
(11) Power amplifier quarter-power resistances.
(12) Valve unit, main terminal strip.
(13) Air supply.
(14) Master oscillator and power-amplifier filament centre-pointing resistances.
(15) Master-oscillator valve.
(16) Power amplifier auto bias resistances.
(17) Aerial coupling coil.
(18) Master-oscillator variometer.
(19) Master-oscillator coil box containing variometer and Selsyn motor.
(20) Amplifier closed-circuit coil.
(21) Master oscillator wave-change switch.
(22) Entry for emergency wave-change handle.
(23) Amplifier closed-circuit wave-change switch.
(24) Aerial coupling-coil wave-change switch.
(25) Wave-change dial.
(26) Aerial tuning-coil wave-change switch.
(27) Wave-change repeater dial.
(28) Aerial tuning coil.
(29) Aerial loading coil (when required).
(30) Aerial lead-out insulator.
(31) Aerial and closed-circuit ammeters.
(32) Amplifier valves.
(33) Valve unit meter panel containing master-oscillator and amplifier plate meters and amplifier grid meter.
(34) Local control panel.
(35) Coil unit, main terminal strip.
(36) Aerial tuning variometer.
(37) Amplifier closed-circuit variometer.

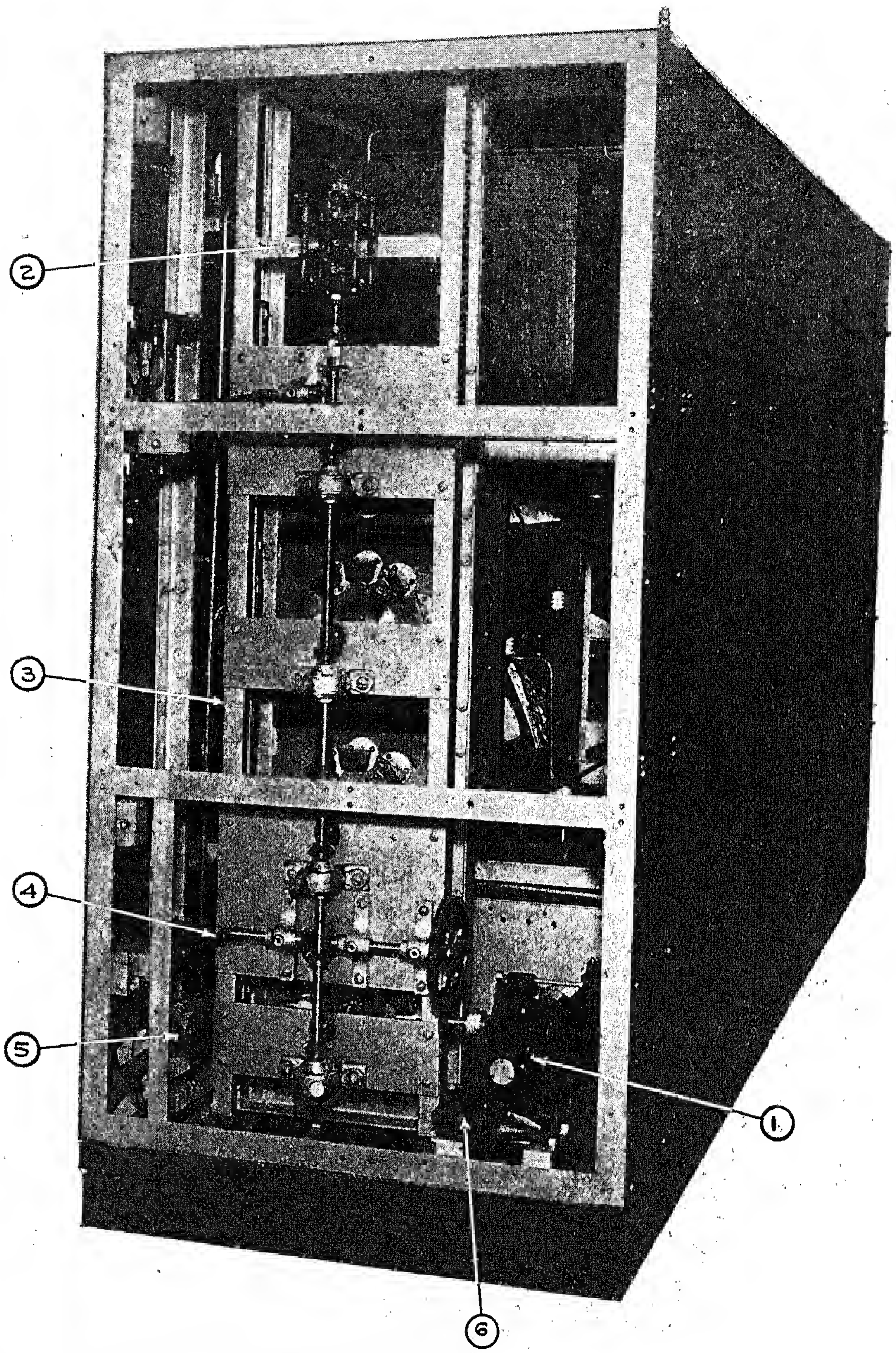


Fig. 11.—End view of medium-wave transmitter, R.M.S. "Queen Mary" (cover panel removed), showing wave-change gear.

(1) Wave-change motor.
(2) Control switches.
(3) Complete assembly of wave-change switchgear.
(4) Hand-control for emergency wave-change.
(5) Wave-change unit main terminal strip.
(6) Wave-change motor fuse.

The main H.T. rectifier is of the 3-phase half-wave type with one hot-cathode mercury-vapour valve per phase. A spare valve is fitted in position and can be switched as a replacement into any of the three phases; its cathode is kept heated to half brilliancy during the period when it is not in use so as to avoid the serious loss of time otherwise involved in "conditioning" a valve which has been lying idle for some time. When first starting up the transmitter at the commencement of a voyage an automatic time delay ensures that high tension is not applied until the rectifiers are properly warmed up by having their filaments alight for 5 minutes.

The long-wave transmitter is identical in design, power, and facilities, with the medium-wave transmitter, except circuits, together with a remotely-controlled mechanism associated with the master-oscillator tuning circuit. The remaining end bay (Figs. 10 and 11) is devoted to the wave-change mechanism.

The method of wave-change used is as follows. The same tuning coils and condensers remain in circuit on all wavelengths, but the active tappings on the tuning coils are changed. In the case of the medium-wave transmitter there are three tuning coils involved—master-oscillator, power-amplifier output, and aerial tuning; while for the long-wave transmitter there is one additional coil for aerial loading. Associated with, and mechanically close to, each tuning coil is a 10-point rotary switch, whose studs are connected to tappings on the

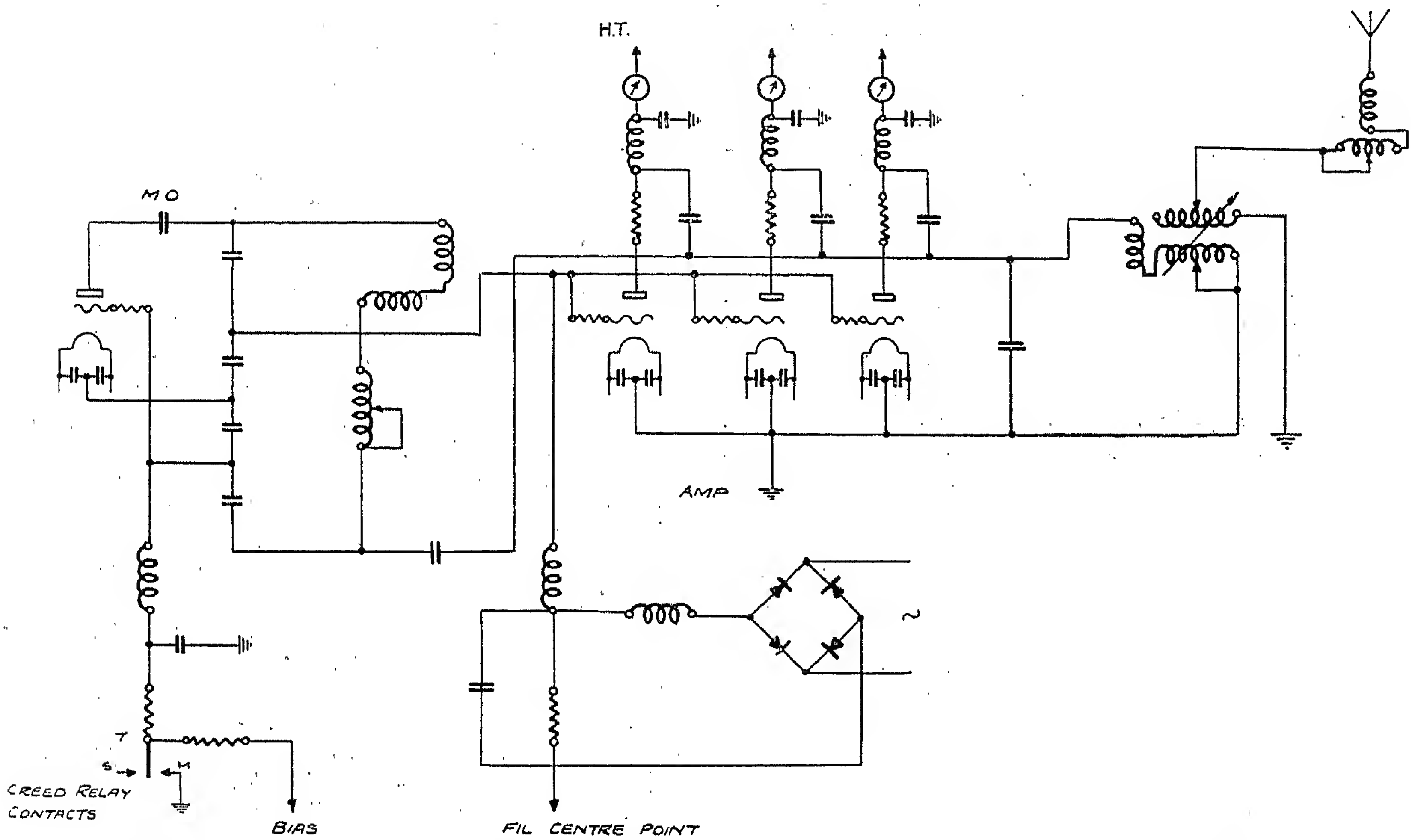


Fig. 12.—Simplified circuit diagram of medium- and long-wave transmitters, R.M.S. "Queen Mary."

for the electrical values of tuning condensers, etc., and the addition of an aerial loading coil. It covers a waveband of 1 875 to 3 000 m., on which, by regulation, transmission is confined to C.W.

As can be seen from the illustrations, the transmitter includes two narrow end-bays flanking three large bays assembled together to form a single unit. The first (end) bay from the left (Fig. 10) contains the air blower, Creed relay equipment, remote-control relay rack, and local-control circuit equipment. In the second bay are housed the main H.T. mercury-vapour valve rectifier with its associated transformers and other power supply gear, together with the dry metal rectifiers for circuit control and grid bias, etc. The third or centre bay contains the master-oscillator and amplifier valves, together with their blocking and tuning condensers, high-frequency chokes, and protective resistances. The fourth bay contains all the tuning coils for both master-oscillator and amplifier coil corresponding to the desired wavelengths. An unusual feature of the switch is that contact between brush arm and stud is made through a special spring-loaded metallized carbon brush with pigtail connection to the brush carrier, the assembly closely resembling the brush gear used on ordinary electrical machinery. All these 10-point switches are operated simultaneously from a common vertical power shaft to which the rotating brush-arms are individually coupled through bevel gears. This common power shaft is itself driven through reduction gear by a small motor which, when idle, has its rotor clamped by a powerful brake and whose starting and stopping is governed by a telephone dial and relay system on principles similar to those used in the design of an automatic telephone exchange.

In addition to the switches just referred to, another group of four 10-point rotary switches are driven from the vertical power shaft. One of these is a pilot switch

connected into the relay circuits to complete the motor-stopping circuits when the switches have travelled to the correct tap-contact position; another ensures that high tension is not applied to the valves unless the h.f. circuits are complete; the third switches auxiliary tuning condensers through a contactor system; while the fourth is used to "indicate back" the position of the switches to the remote-control position.

The common power shaft also furnishes drive to an illuminated indicator disc marked for each position with the frequency and dial number of the wavelength to which the transmitter is then set. In the event of failure of the shaft-driving motor it is possible to operate the shaft through a free-wheel device by means of manual control from the front of the transmitter.

The control circuits are so arranged that if a new wavelength is dialled while the transmitter is running, i.e. with anode H.T. "on," in order to safeguard the valves the H.T. supply is automatically disconnected before there is any movement of the power-driven wave-change group of switches, and is restored when these switches have reached the position corresponding to the number dialled. The time taken to change wavelength depends on the amount of travel of the rotary switches, and in the extreme case of changing, say, from wavelength "3" to wavelength "2," which involves the maximum travel (since the switches always rotate in the same direction, and must therefore traverse 9 positions for the case quoted) this total time does not exceed 10 seconds. For changing in the opposite direction, i.e. from wavelength "2" to wavelength "3" the time is about 2 seconds. The control mechanism embodies a storage feature whereby it is impossible for a second operation of the dial to have any effect unless the changes governed by the first operation have been completed. If the dial is operated to give the same wavelength as that on which the transmitter is already set, there is no movement of the rotary switches, the only effect of the second dialling being a momentary interruption of the H.T. supply. Dialling may be done either on the "local control" dial mounted on the front of the right-hand bay of the transmitter (Fig. 10) or on another dial located at a distance on a remote-control unit.

It sometimes becomes desirable to change a wavelength very slightly from its pre-set value, say by a few hundred cycles, in order to avoid interference with or from other stations working on the same wavelength. To meet this possibility a small auxiliary variometer is included in the master-oscillator circuit, and is varied at the remote control through a "Selsyn" system to give the desired small frequency change, the switch-selected taps and the master-oscillator and other coils being left unaltered. This system consists, in effect, of two small a.c. synchronous-motor mechanisms, electrically interconnected so that the rotor of the "receiving" end, coupled to the variometer, does not rotate but takes up a steady position corresponding to the hand-controlled position of the rotor at the transmitting end, i.e. on the remote-control panel.

On the front of the left-hand end bay (Fig. 10) are switches of the telephone pattern which operate through relays to give the following controls: "H.T. on-off," "Full, half, or low power," "C.W. or M.C.W.," and "Local" or "Remote" control. This last switch provides for the transfer of all the other switch facilities just mentioned, together with the signalling key and wave-change dial circuits, to a remote-control unit. In the case of the "Queen Mary" this remote-control unit is situated in the operating room 400 ft. from the transmitter.

The remote-control unit is of panel type and is mounted on one of the "operators' position" racks in the operating room. It is equipped with a telephone dial for wave selection, wavelength number repeater to indicate the wavelength on which the transmitter is set, and switches for H.T. supply, etc., as on the "local control" position on the transmitter. It also includes the control for the "Selsyn" system, which governs the position of the master-oscillator auxiliary variometer, and permits fine regulation of the transmitting frequency on either side of its normal value.

(3.5). Short-Wave Receiver.

Receiving equipment for the larger passenger liners, in which the long-distance "public" communication services are of great importance, is necessarily of a much higher grade than the simple receivers mentioned in Section (2.3), though the band of wavelengths to be covered remains unaltered at from approximately 15 m. to 20 000 m. In order to obtain efficiency and ease of control no attempt is made to cover this enormous band in one receiver, specialized receivers of more limited wave-range being used.

The receiver units from which the "Queen Mary's" equipment is built up consist of the "short-wave" receiver, wave-range 13·5–550 m., primarily used for short-wave telegraphy and telephony; the "medium-wave" receiver, wave-range 500–3 000 m., for medium- and long-wave telegraphy; and "long-wave" receiver, wave-range 1 750–20 000 m., for long-wave telegraphy. These receivers are all of the rack-mounted type and have the following features in common:—

(*a*) Power supplies drawn from an a.c. power unit.

(*b*) Single-control tuning with large indicator drum (8 in. diameter) calibrated directly in kilocycles, the calibration track covering 280°.

(*c*) Auxiliary note filters for heterodyne reception.

(*d*) Auxiliary preselector circuit which can be switched in or out as desired.

(*e*) Output circuits arranged for loud-speaker monitoring, operating a tape recorder for morse telegraphy, and direct feed to the terminating equipment for telephony. For ordinary reception of morse signals a fixed 13-db. attenuator is inserted before the headphones, so that both headphones and loud-speaker or tape recorder can be energized simultaneously at their suitable different levels.

Fig. 13 shows a single short-wave receiver mounted on a rack, together with its associated preselector and power supply units, while Figs. 14 and 15 show the circuit diagrams of the receiver and preselector units respectively. The circuit is of the superheterodyne pattern, requiring 9 valves for the following functions; one h.f., 1st detector, separate beating oscillator, two I.f. stages, 2nd detector, l.f. output valve, separate heterodyne oscillator, and separate automatic gain-control valve. This receiver is particularly designed for use on large

liners, and possesses accordingly a number of rather special features. These are:—

(1) The short-wave receiving aerials must be so situated as to be as free as possible from the numerous sources of electrical noise which are normally encountered on board such vessels. This in general means that the aerial is at a fairly large distance from the receiver room, and must be connected thereto by a transmission line, which if of the open-wire pattern is itself liable to pick up noise. It is therefore necessary to provide special circuits for coupling the receiver through the transmission line to the aerial. In the present case the required

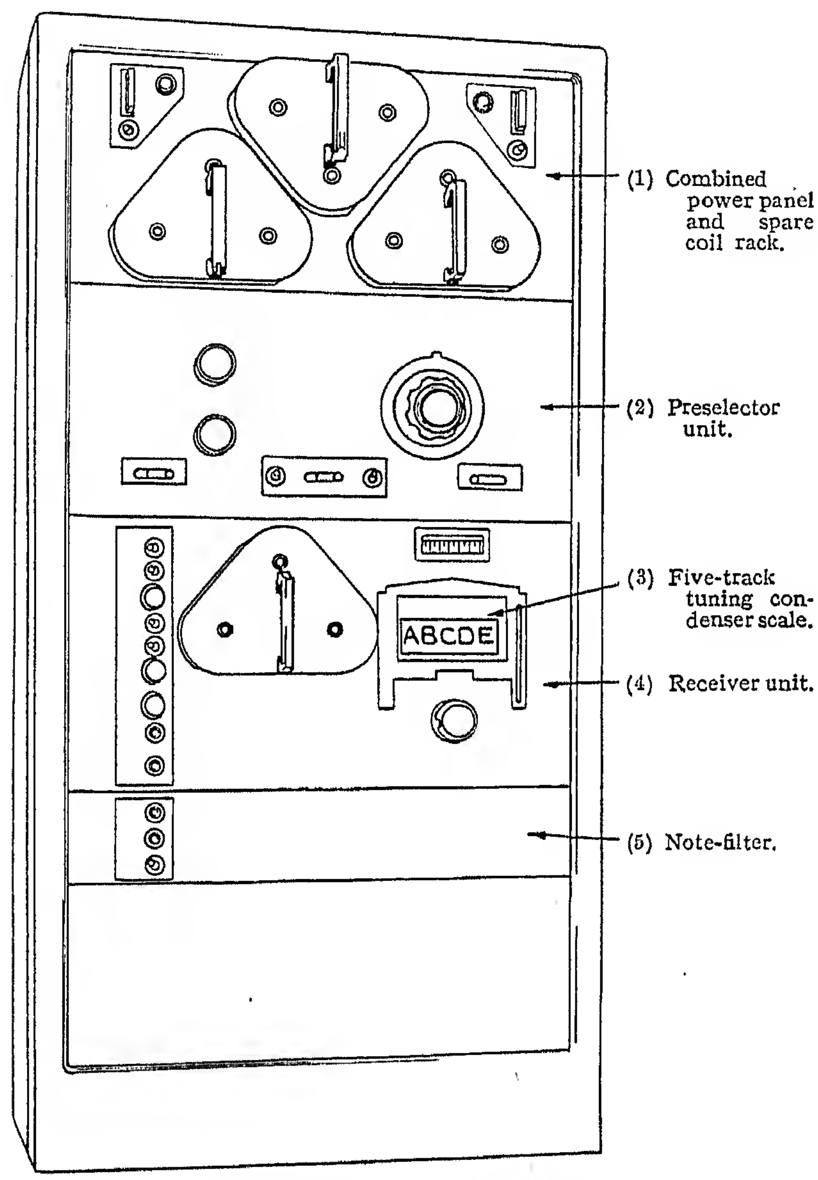


Fig. 13.—Rack-mounted short-wave receiver used on R.M.S. "Queen Mary" (waveband 13·5-550 m.).

coupling circuits are included in a separate preselector panel unit, which serves simultaneously to match the receiver proper to the aerial transmission line, to give extra selectivity against transmissions on a neighbouring frequency, and to give almost complete suppression of medium- and long-wave voltages picked up by the aerial. It will also give an accurate balance against any noise currents which may be picked up in the transmission line if the latter is of the balanced open-wire type.

(2) A single high-efficiency h.f. stage is provided. High efficiency is necessary to ensure that valve noise shall be low compared with the signal, and to give adequate second-channel suppression.

(3) For heterodyne reception with note filter it is

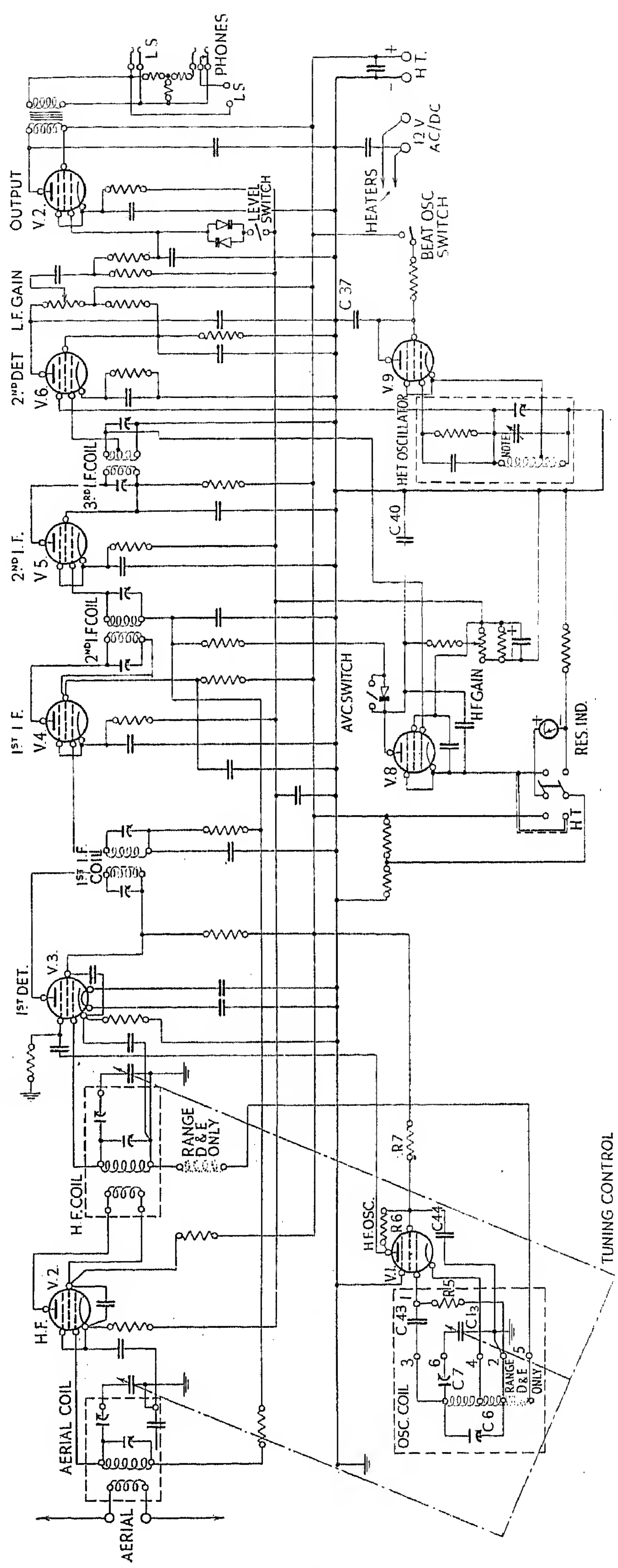


Fig. 14.—Circuit diagram of short-wave receiver unit.

necessary that the h.f. beating oscillator remain very constant in frequency. The high-tension supply voltage for the whole receiver is therefore held constant by a "stabilovolt" gas tube, which gives a stable heterodyne note despite changes in the settings of any control other than tuning and also despite large fluctuations in field strength of the incoming signal.

(4) In order to obtain maximum efficiency, plug-in coils are used. Five sets cover the complete wave-range of 13·5–550 m., the range of a set on the shorter wavelengths not exceeding a 2/1 ratio. Speed and correctness of handling is ensured by ganging each set of coils, while the appropriate directly-calibrated track on the large indicator drum is automatically illuminated when a coil unit is inserted.

(5) The automatic gain control can be set to operate with either of two time-constants, one being symmetrical and suitable for telephony, the other asymmetrical and suitable for telegraph reception. It is extremely efficient, a signal variation of 1 μV to 100 000 μV (100 db.) of constantly modulated carrier input being stabilized to 8 db. variation of audio output.

(6) Tuning is facilitated by a resonance meter operative on either telephony or telegraphy.

(7) An output limiter is provided to attenuate powerful static crashes.

(8) The intermediate frequency is 350 kc., this being the least likely to experience any form of interference during ocean service.

(9) The sensitivity is such that a 30 per cent modulated signal of 0·5 μV in the aerial transmission line can give at least 50 mW of low-frequency output from the receiver at all frequencies.

(10) The band width is 8 kc. for 6 db. loss, and 30 kc. to 35 kc. for 60 db. loss.

(3.6). Medium- and Long-Wave Receivers.

The general appearance of the medium- and long-wave receivers is similar to that of the short-wave receiver, except that no plug-in coils are used. The medium-wave receiver covers a waveband of 500–3 000 m. in two ranges, with switch selection, while the long-wave receiver covers a waveband of 1 750–20 000 m. in three ranges. Both sets are of the straight type, using 6 valves arranged for two stages of h.f. amplification, detector, two l.f. amplification stages, and separate heterodyne oscillator. (The tuning condenser of the heterodyne oscillator is ganged with the other tuning circuits.) Figs. 16 and 17 show the circuit diagrams of the medium-wave receiver and preselector units. Some of the more important considerations affecting the design of both these receivers are as follows:

(1) The choice of the "straight" circuit is due to the extreme amount of pre-selectivity which is necessary to permit satisfactory medium- or long-wave duplex operation on frequencies differing by less than 10 per cent. In these receivers about two-thirds of the over-all selectivity precedes the first valve for duplex operation. Incidentally, as these receivers are used only for telegraphy there is no need that they should pass a definite or constant band width, and note filtering increases still further the effective selectivity.

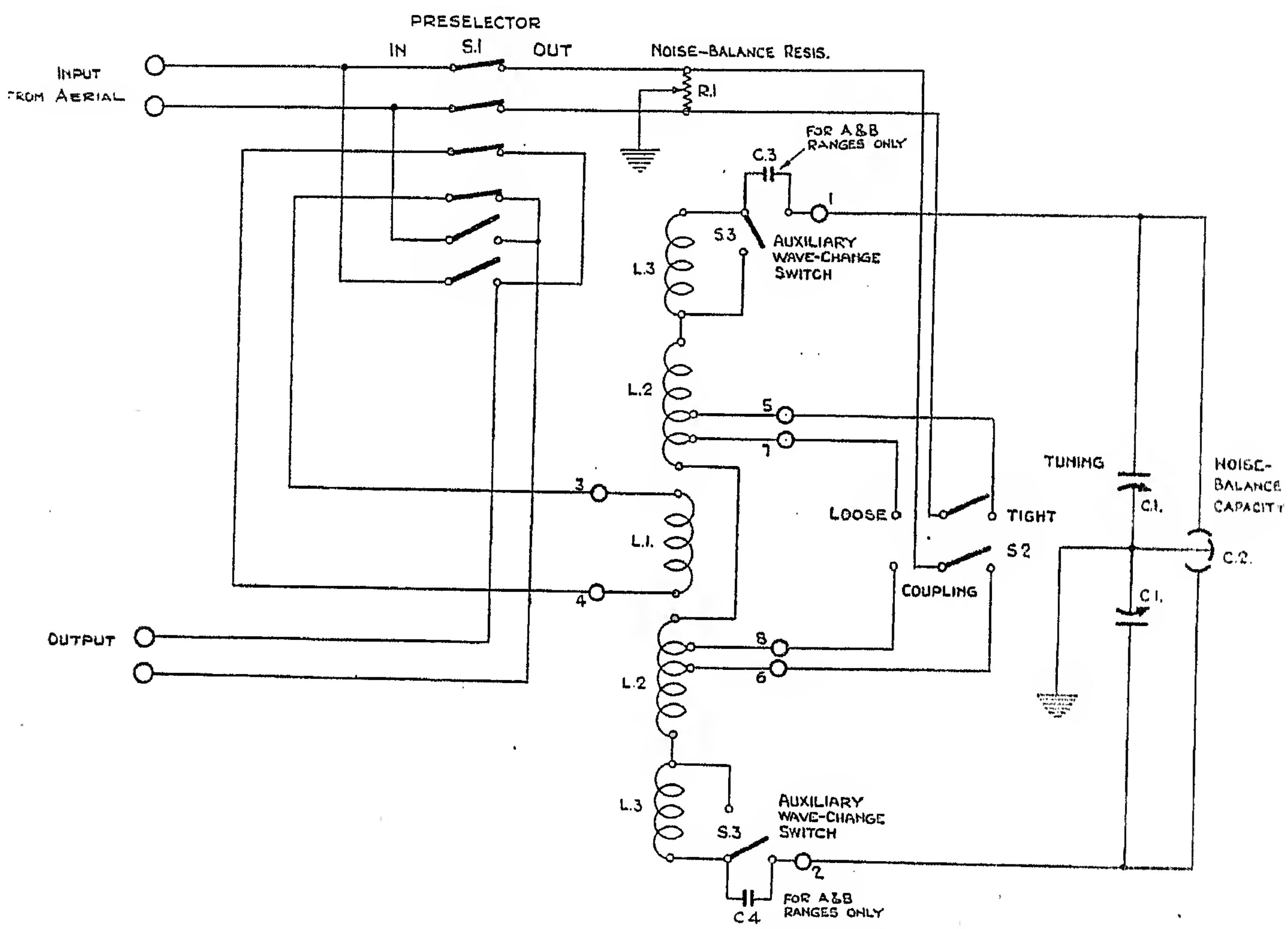


Fig. 15.—Circuit diagram of short-wave receiver preselector unit.

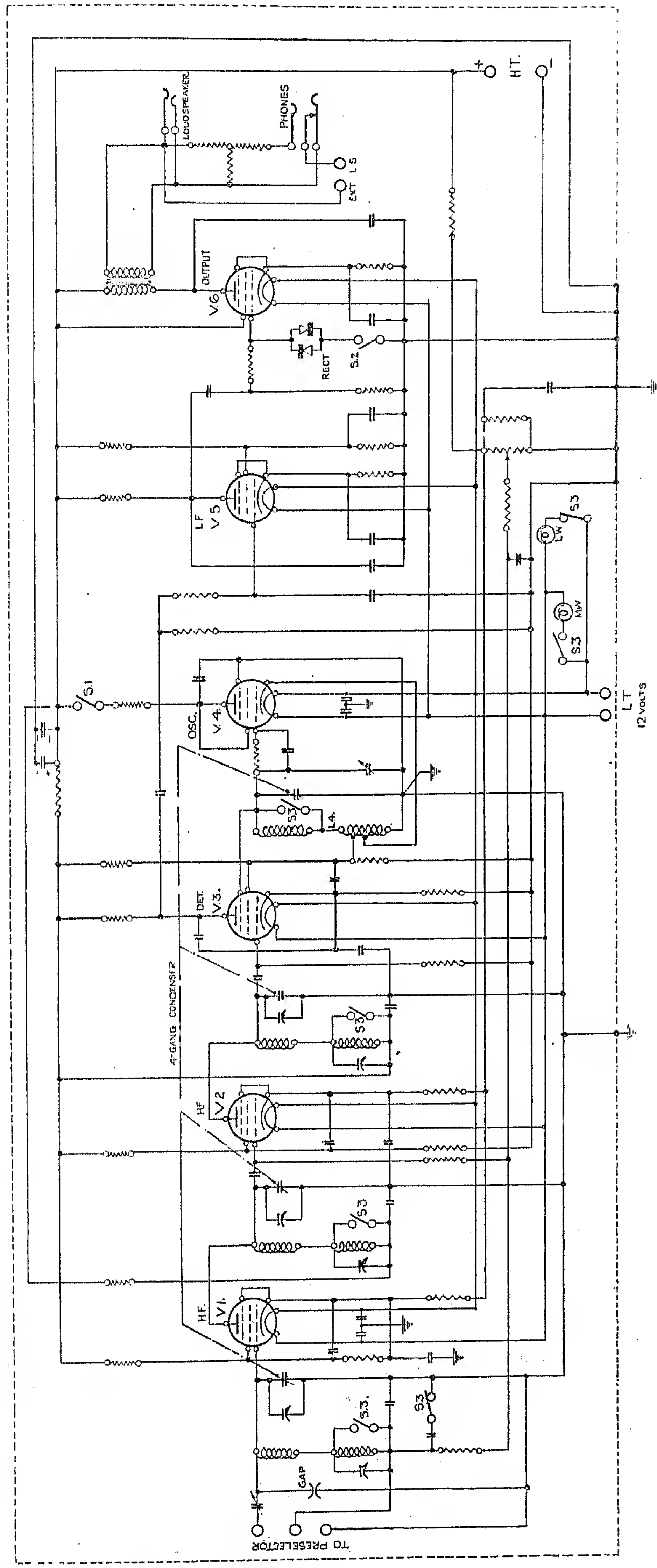


Fig. 16.—Circuit diagram of medium-wave receiver unit.

(2) Both the receiver proper and its associated preselector panel are provided with adjustable input coupling condensers. Following the condensers are vacuum-gap arresters set to break down at 1 000 volts in the case of preselector, and at 500 volts in the case of the receiver. By means of the input condensers the signal coupling can be increased up to the point where voltages induced by the local transmitters become prohibitive.

(3) The preselector units contain three tuned circuits. The first valve is therefore preceded by a total of four tuned circuits, and followed by two others. The preselector units are built throughout with components

(6) " Crash limiting " is provided as in the short-wave receiver.

(7) In order to permit of simplex (break-in) operation on a common wavelength, an overload bias device is provided on the first valve.

(8) The sensitivity of each receiver is such that on C.W. telegraphy the low-frequency output is 50 mW for under 5 μV input. Satisfactory headphone operation is possible with signals of less than 1 μV.

(9) When combined with its preselector, each receiver has a signal frequency selectivity equivalent to an attenuation of more than 100 db. at 10 per cent off signal

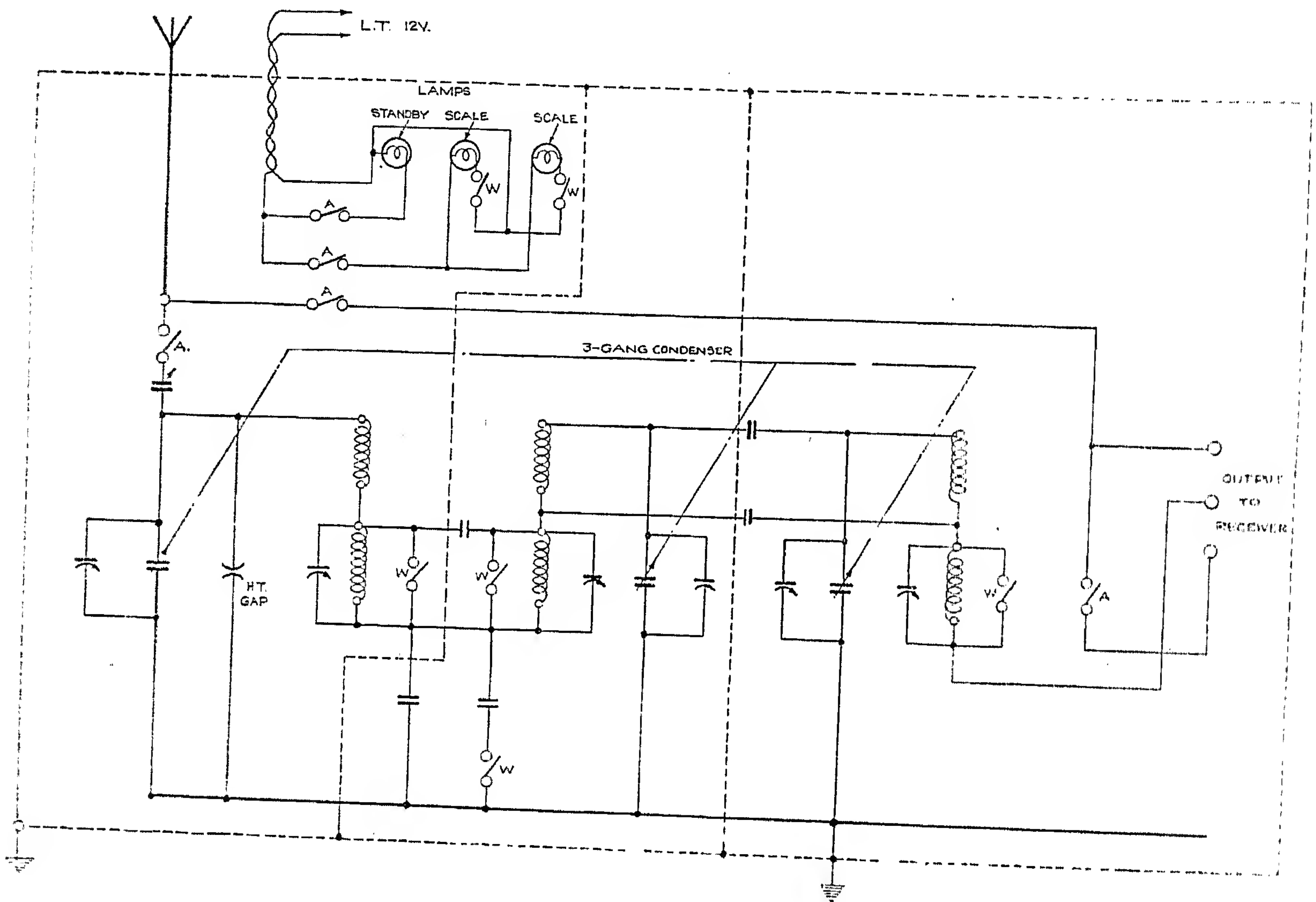


Fig. 17.—Circuit diagram of medium-wave receiver preselector unit.

which can withstand approximate 2 000 volts (r.m.s.) at radio frequency, since the aerial vacuum-gap arresters must not operate continuously and so set up interference to adjacent receivers on all frequencies. Continuous operation of the arresters following the preselector is not usual, and in any case could set up only very small external interference on other frequencies than that to which the receiver is tuned.

(4) When the preselector is thrown out of circuit a lamp is lit to indicate that the band width passed is suitable for stand-by reception. This feature is of special importance for the 600-m. watch.

(5) Wave-change switching is provided on both receivers and preselectors, and the correct tracks on the frequency-calibrated indicator drum are automatically illuminated.

frequency. The note filter, of course, still further augments the total selectivity.

(3.7). Terminating Equipment.

With the advent of the subscriber's ship-to-shore radiotelephone service a new item has had to be added to the types of equipment required for ship installation. This new item is the " terminating equipment," which in one form or another is a regular part of all radio-link telephone circuits. The primary function of terminating equipment is to prevent local interaction between the radio transmitter and radio receiver, despite their being deliberately coupled together through the subscriber's apparatus and also unavoidably coupled together by induction from aerial to aerial. In the absence of terminating equipment the effect of these couplings is,

in extreme cases, to set up actual "singing" round the circuit, and in less extreme cases to reduce the effective sensitivity of the receiver and to impair the quality of both transmitted and received speech. In addition to preventing this local interaction, terminating equipment may also include some "privacy" system which renders the radiated speech unintelligible to unauthorized listeners.

Although ship-to-shore telephony has been established for some years, it has been customary to keep the terminating equipment down to the minimum consistent with a good speech circuit, and the privacy feature has not been a regular part of the service. In the case of the "Queen Mary," however, it was considered that the service should be of the same nature as that furnished on the transoceanic links, and the terminating equipment is accordingly not only rather more complete than that hitherto fitted in ships but also includes a privacy system. Since the underlying principles are the same in all cases, the following notes on the "Queen Mary" equipment may be taken as including the main features of the more limited equipment used in older ships.

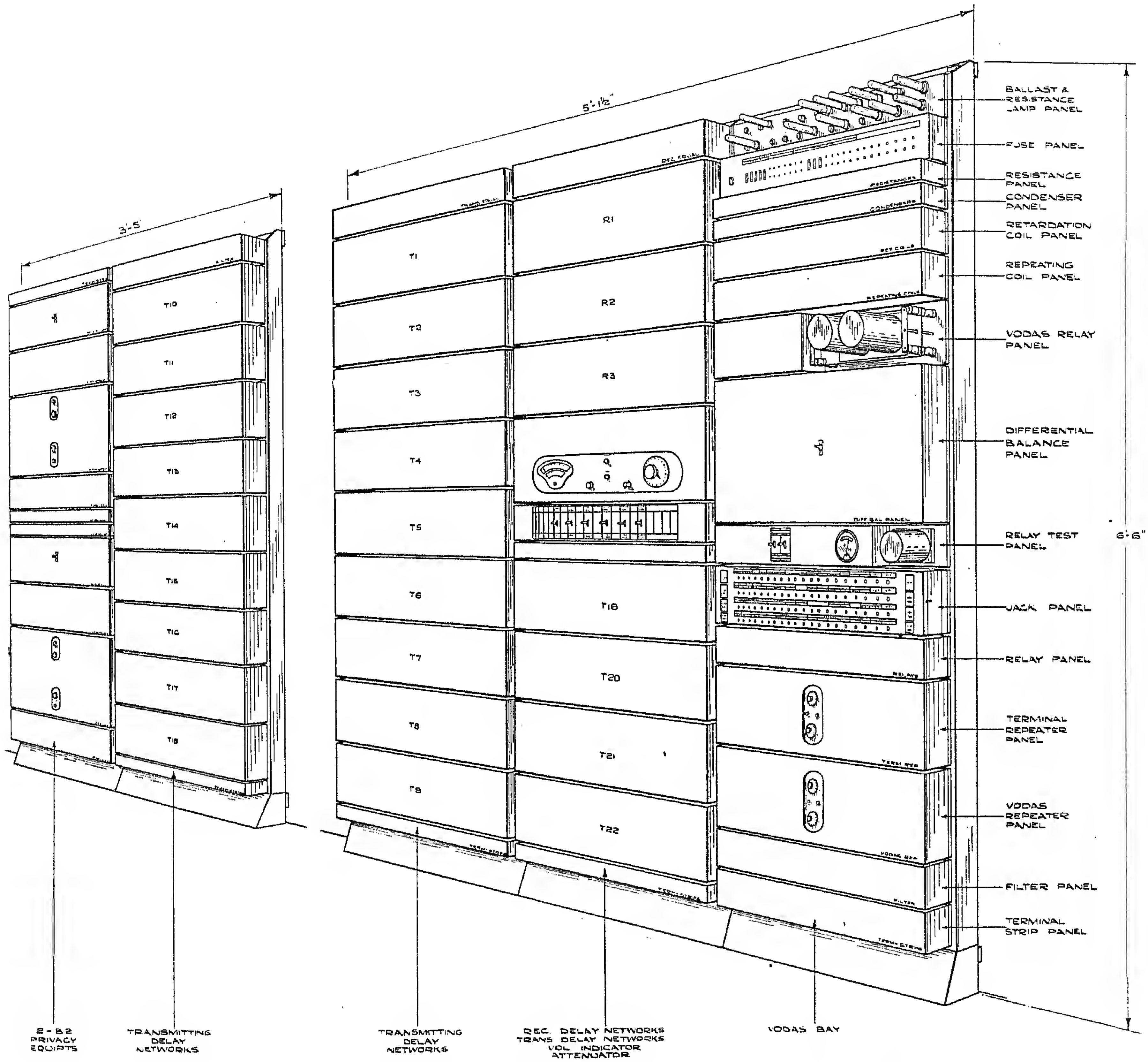


Fig. 18.—Rack assembly of terminating equipment on R.M.S. "Queen Mary."

Fig. 18 shows the rack assembly of the complete terminating equipment, including the privacy portion. Its construction follows normal telephone practice, the only special mechanical feature being in the fixing of the rack

to the ship members through a rubber anti-vibration mounting. The privacy portion of the equipment includes five indirectly-heated valves, the remainder, i.e. the terminating equipment proper, using a total of 17 repeater valves of the 0·25 A filament type. All power supplies are derived from the a.c. supply to the station.

The fundamental operation of terminating equipment is automatic switching of the transmitter carrier, and of the receiver, under the influence of the subscriber's voice, the transmitter being switched "off" and the receiver left "on" at full sensitivity when the subscriber is listening to the distant point, while the reverse action occurs when the subscriber speaks to the distant point. In other words, the radio circuit is effectively operated on a simplex basis, preventing the formation of a "singing path." The switching is performed by means of a voice-operated detector amplifier (see Figs. 19 and 20) operating a fast relay train in the radio transmitter. At the same time as the carrier is switched on, a blocking device is inserted in the receiving circuit so that no singing path can exist (in the case of 2-wire P.B.X. working) round the local loop consisting of hybrid coil, radio transmitter, radio receiver, hybrid coil. The relay train is arranged to have a "hangover" of about 150 milliseconds, i.e. the relays do not release until the lapse of that time after the speech has finished. This prevents any unpleasant echo effects, due to the reflections at the far end, from reaching the speaker.

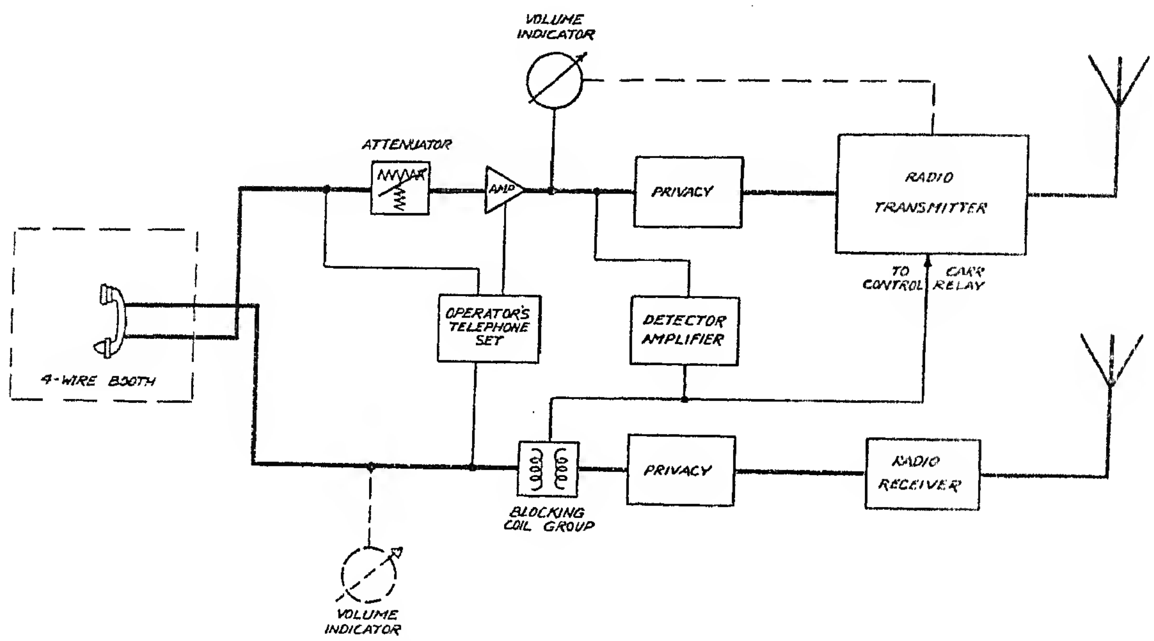


Fig. 19.—Block diagram of 4-wire radiotelephone circuit with half singing-suppressor equipment on R.M.S. "Queen Mary."

The voice-operated detector-amplifier controlling the carrier is fitted with a sensitivity control which can be set to suit the conditions existing at any given moment. The sensitivity should be such that the relay train is just operated by the initial weak parts of the speech, and thus "clipping" is prevented. If the sensitivity is made too great, false operation due to room or line noise will occur, causing the local carrier to come on and cutting off the received speech. After a little experience the operator is able to adjust the sensitivity correctly without any difficulty.

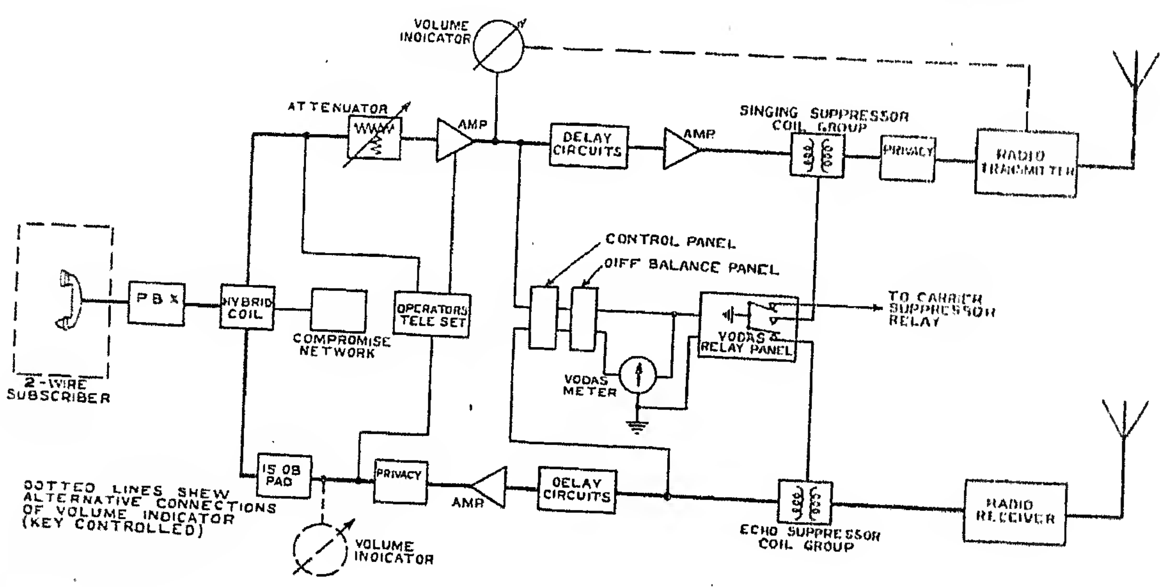


Fig. 20.—Block diagram of 2-wire radiotelephone circuit with full singing-suppressor equipment on R.M.S. "Queen Mary."

A voice-frequency amplifier and a manually-operated

gain control are also provided, so that allowance can be made for varying subscriber's levels. This enables the detector-amplifier to be operated at the correct level and thus prevents possible "clipping," and also enables the modulation of the transmitter to be kept at the correct value.

When the ship's transmitter is setting up a very strong field at the shore receiver, the action of the carrier-suppressor device will cause slight "plops" to be heard by the land subscriber when the carrier comes on, due to the action of the A.V.C. on the receiver. These are not sufficiently loud to be objectionable, but they cause trouble when the circuit is being extended via another radio link. Under such conditions, the transmitting and receiving frequencies must be separated sufficiently to enable the carrier-suppressor device to be removed.

An equipment of the type shown in Fig. 19 is known as a "half" V.O.D.A.S. (voice-operated device, anti-singing) equipment, and covers the essentials in all cases where the ship terminal is operated on a 4-wire basis. It can also be used on a 2-wire basis, provided that the radio path is stable. The usual telephone supervisory and monitoring facilities of course are also provided, but these are purely auxiliary features.

When the ship subscriber is connected in the normal 2-wire manner, additional complications arise, since this means the introduction of a hybrid coil to effect the junction between the transmitting and receiving paths. A hybrid coil is a special type of differential transformer whose windings, in conjunction with the subscriber's line and a balancing network of equal impedance to the line, furnish an a.c. bridge the diagonals of which are connected, directly or inductively, one to the transmitting path and one to the receiving path; the two paths are thus effectively separated if the bridge is perfectly balanced, although both are connected to the subscriber's line. It is, however, fundamental in the use of a hybrid coil that (the balance between line and network never being perfect) there remains a certain transference of energy across from the "receive" path to the "transmit" path. This is a source of trouble, for two reasons. Firstly, if the received level is allowed to become too high, the fraction of signal which is transferred across the hybrid coil may be sufficient to operate the transmitting detector-amplifier, with consequent re-transmission of the received signal and, in certain circumstances, the setting-up of an undesirable echo at the far end. Secondly, this re-transmission may actuate the blocking device in the receiving side, thus cutting off the received signal.

Now, although a good hybrid balance is obtainable on a ship, re-transmission can easily occur if the received signal is fading to a greater extent than the receiver A.V.C. can control. The second effect also occurs if the radio noise-level is very high, since a proportion of this noise will be transferred across the hybrid coil and will cause a similar false operation.

The possibility of such re-transmission occurring is therefore guarded against on the "Queen Mary" by the installation of a full singing-suppressor equipment. This equipment is so arranged that it can be switched instantly into either of the two radiotelephone channels, it being assumed that conditions will nearly always be good enough to allow of one circuit being operated satisfactorily with the half singing-suppressor equipment.

The equipment consists essentially of two detector-amplifiers (one in each side of the circuit) with their relay trains and suppressing devices, delay networks to hold up the speech long enough for the relays to operate, and amplifier to make up the various losses in the circuit. The control of the carrier-suppressor relays is transferred from the original detector-amplifier to the detector-amplifier in the full singing suppressor when the latter is switched into circuit.

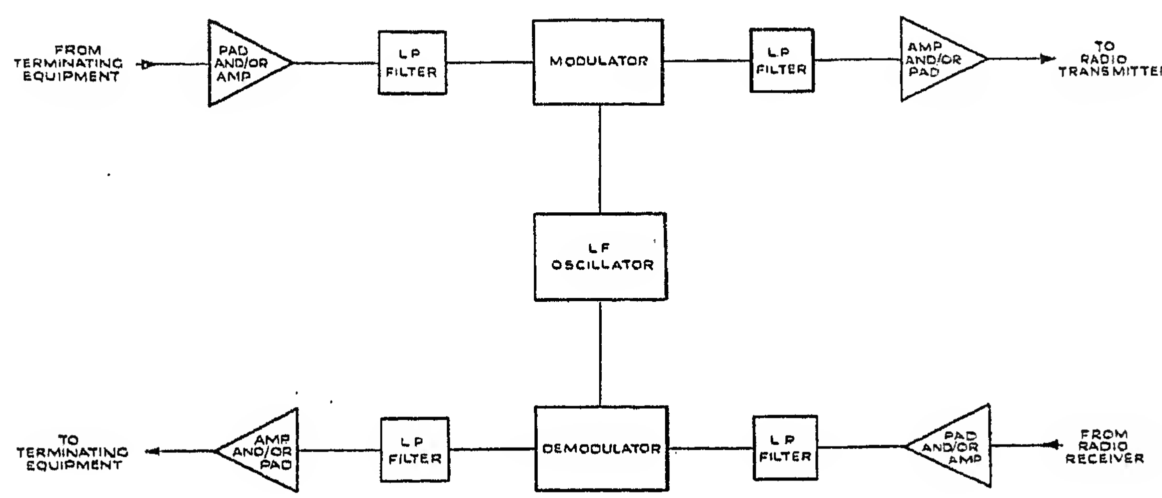


Fig. 21.—Block diagram of privacy equipment on R.M.S. "Queen Mary."

The operation of the equipment (see Fig. 20) is then as follows. Speech from the passenger passes across the hybrid coil and through an attenuator and amplifier. By means of the manually-operated gain control the operator adjusts the passenger's speech to zero level (i.e. 5·9 mW) at the output of the amplifier. The speech then passes through a number of filter sections, so designed that they produce a delay of 22 milliseconds in the speech, irrespective of frequency. These delay filters have a loss of approximately 30 db. and are followed by a further amplifier to make good this loss.

Bridged across the main circuit ahead of the delay filters is the transmitting detector-amplifier, of input impedance such that it introduces no appreciable loss. This detector-amplifier takes a small part of the speech currents, amplifies them in a 3-stage amplifier, and then rectifies them. The resulting direct current is used to

operate a train of three very sensitive polarized relays mounted on anti-vibration pads. Operation of these relays opens the transmitting path to the outgoing speech, blocks the receiving path, and switches on the carrier in the same manner as in the half singing-suppressor system. The circuit is so arranged that the delay introduced by the special networks also covers the switching-on of the carrier, rendering the possibility of "clipping" still more remote than in the case of the half singing suppressor, where freedom from "clipping" is governed by the sensitivity of the detector-amplifier and the "quick-starting" properties of the radio carrier.

Consider now incoming speech being received on the ship. This passes through the receiving side of the singing suppressor and in doing so operates the receiving detector-amplifier, which paralyses the transmitting detector-amplifier so that any speech being transferred across the hybrid coil does not operate it. The existence of the receiving detector-amplifier thus renders it possible to work the circuit on a 2-wire basis when the hybrid unbalance and the noise-level would otherwise make it impossible. The two detector amplifiers, transmitting and receiving, are made up as one unit known as the "differential balance panel."

The full singing-suppressor equipment is set up to work at zero equivalent (i.e. introducing neither gain nor loss) on both sides, so that its insertion or removal does not disturb the circuit.

The circuit is, of course, permanently monitored by the operator, who has a volume indicator in front of him which enables him to check outgoing and incoming levels, both of which can be adjusted by controls conveniently located. In addition, by the operation of a switch, the volume indicator acts as a modulation meter connected to the output of the radio transmitter so that the operator can occasionally check that the modulation depth is remaining at the correct average level. When the full singing-suppressor equipment is in use, an additional meter indicates that it is working satisfactorily. This meter, which is a centre-zero galvanometer, deflects to the right on outgoing speech and to the left on received speech.

Provision is made for the operator to talk either to the ship subscriber or to the distant operator, or to both simultaneously, by radio. He also has ring-back facilities to the ship subscriber. For the initial lining-up of the circuit the operators' control positions are equipped for either C.W. or M.C.W. telegraph operation as alternatives to speech. A special "weighted" amplifier, i.e. one whose frequency response curve instead of being flat is adjusted to resemble that of the human ear, is provided for measuring signal/noise ratios; its gain control is calibrated directly in decibels.

The whole of the voice-control equipment, with the exception of the controls which are located at the receiver control positions, is mounted on four 6-ft. single-sided racks carrying standard 19-in. panels (Fig. 20).

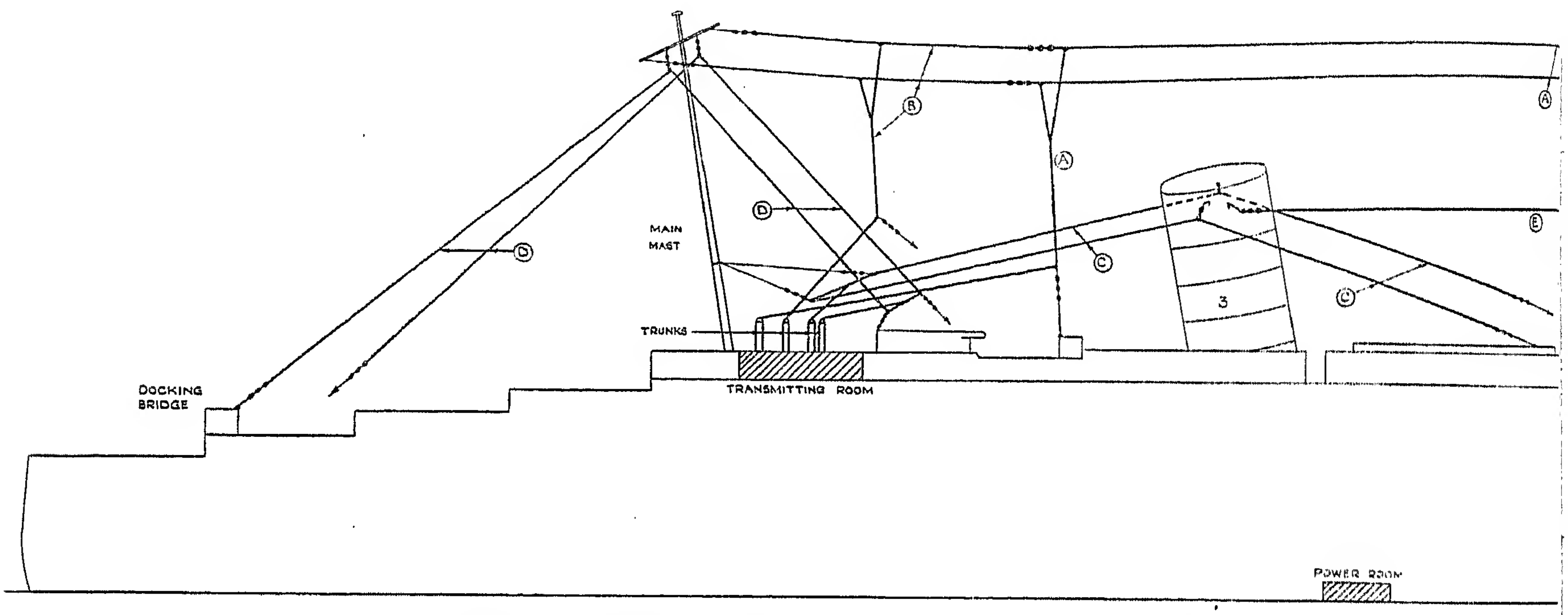


Fig. 22.—Outline of R.M.S. "Queen Mary," showing position of radio plant and aerials.

(A) Long-wave transmitting aerial.
(B) Medium-wave transmitting aerial.
(C) Short-wave transmitting aerial (No. 1).
(D) Short-wave transmitting aerial (No. 2).
(E) Emergency and long-wave receiving aerial.

The privacy portion of the terminal equipment is, in the case of the "Queen Mary," supplied in duplicate so as to provide for two simultaneous radiotelephone channels. The two equipments are mounted on a common rack, the layout of which is shown in Fig. 18. The principle of operation (see Fig. 21) is to invert the speech at the sending end so that low frequencies become high, and vice versa, the speech being re-inverted at the receiving end. This inversion is obtained by modulating the speech with a fixed frequency lying outside the voice range, and then selecting by filters the appropriate sideband.

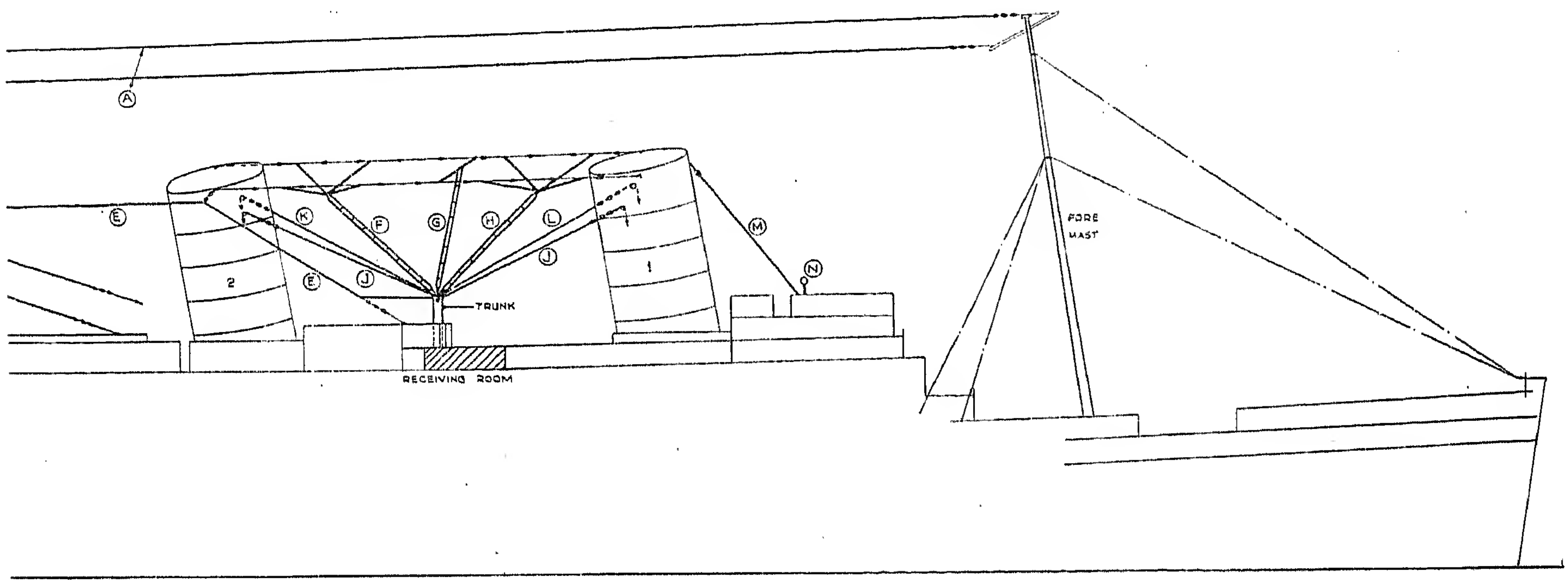
The system is operated on a 4-wire basis, i.e. a separate modulator, together with its associated amplifiers and filters, is used in each direction of transmission. A constant-frequency oscillator supplies the necessary carrier to the modulator and demodulator in the two sides of the circuit, the three units being combined in practice into an "oscillator-modulator" panel. In addi-

tion to this panel there is an amplifier, a filter panel, and a mains supply panel. The amplifier enables the privacy equipment to be operated at zero equivalent, while input filters limit the voice-frequency range to 2 750 cycles, and output filters cut out unwanted higher modulation products.

The insertion of the privacy equipment is controlled by two keys, one for the transmitting side and one for the receiving side, so that the system can be used in either or both directions of transmission as required. At the same time as the transmitting inverter is switched on, an a.c. motor in the transmitter is started up. This motor drives a subsidiary tuning condenser, which causes the carrier frequency to "wobble" through a certain predetermined band width; without this "wobbling" it might be possible for speech to be received, despite the inversion, on a simple heterodyne receiver.

no practice which is recognized as standard, and large differences are found between the layouts adopted in different ships, according to date of installation, supplier, legal requirements of the country in which the ship is registered, etc. It is, moreover, not always possible to achieve a preferred layout; this is particularly noticeable when extending the services of a ship which is some years old and in which accommodation for additional equipment is difficult to obtain. In the case of R.M.S. "Queen Mary," however, no such difficulty was present, and the station layout described below may be considered as satisfactorily meeting the technical requirements current at the time of installation.

Attention has been drawn earlier in the paper (Section 1.81) to the growing practice of regarding direction-finders as bridge instruments. This practice has been adopted in the "Queen Mary," in which ship the



(F) 13 Mc. double dipole.
(G) 17-Mc. dipole.
(H) 8-Mc. double dipole.
(J) 4-Mc. dipole.
(K) Medium-wave receiving aerial.
(L) Broadcast receiving aerial.
(M) Direction-finder sense aerial.
(N) Direction-finder loop.

(4) R.M.S. "QUEEN MARY" RADIO STATION

(4.1). General.

The preceding Sections of this paper have been devoted to the radio services now in operation in the mercantile marine, and to the main items of equipment required for carrying on these services. It remains to deal with the ship station as an entity by itself, formed of the equipment items previously described, together with their auxiliaries such as power supply sources, aerials, etc.

In the great majority of cases the ship "radio station" is a very simple affair, consisting of a single room, as high above the water line as possible, in which is installed all the apparatus. Usually a single aerial serves for both transmission and reception, either switched over by hand or automatically switched by the keying circuit for "break in" operation.

In the case of the "express steamer" class of vessel a very different picture is presented, with equipment in widely separated rooms, using anything up to a dozen or more aerials, and usually interconnected through an elaborate operating control network. There is as yet

direction-finder is an entirely independent unit, even to its power supplies. It has therefore been described separately in the above-mentioned Section, and is not dealt with as part of the radio station proper, whose function is primarily that of communication.

The communication equipment is housed in three separate places on the ship, viz:—

(*a*) The power room, situated near the engine room of the ship, containing the two 45-kVA motor-alternators for supplying all power to the transmitting and operating rooms.

(*b*) The transmitting room on the sun deck, containing the four main transmitters and the power control and distribution board.

(*c*) The operating room, also on the sun deck, about 400 ft. away from the transmitting room, containing all receivers, telephone terminal equipments, remote-control apparatus, transmitting keys, high-speed transmitting and receiving apparatus, and a complete emergency station.

Fig. 22 shows an outline of the ship, giving the respective positions of these rooms and of the aerial system.

(4.2). Power Room.

The power plant is situated in a small fireproof compartment adjacent to the ship's engine room, and is in duplicate. It comprises two 45-kVA, 220-volt, 50-cycle, 3-phase a.c. motor-alternators, driven off the ship's 220-volt d.c. mains, with automatic starters remote-controlled from the power board in the transmitting room.

The machines are of naval pattern all-steel, single-yoke construction, each weighing about $2\frac{1}{4}$ tons. Only one is in use at a time, running normally at about half load, the maximum demand being two-thirds of the full-load capacity; the other machine is a spare. Normally, one machine is running during the westbound and the other during the eastbound voyage, to equalize wear. There is thus ample reserve power for any future extension of the radio station.

The a.c. supply here generated feeds not only the transmitters but also all the receivers and terminating equipment; it furnishes in addition the normal lighting supply for the operating room, and battery-charging supply for the emergency equipment.

(4.3). Transmitting Room.

This is situated at the after end of the sun deck, just forward of the mainmast, and measures some 30 ft. by 14 ft. by 9 ft. in height; the layout is shown in Fig. 23. The equipment in this room weighs about 11 tons and comprises:—

(*a*) *A Power Control and Distribution Board.*—This board, which is of steel throughout and measures approximately 7 ft. × 5 ft. × 2 ft. 6 in. deep, carries duplicated stop-start motor and alternator control arrangements for the two main motor-alternators (which are seven decks below), together with the necessary pilot lamps, voltmeters, ammeters, frequency meter, and an automatic voltage regulator which keeps the 3-phase a.c. supply at a constant voltage irrespective of the load or temperature conditions. The board also carries the control for the modulating motor-alternator used with the medium-wave transmitter. The 50-cycle 3-phase a.c. supply is distributed to 6 output circuits, each having its own switch and pilot lamp—one to each of the four transmitters, one to the receiving room, and a spare.

(*b*) *A Medium-wave Telegraph Transmitter* [described in Section (3.4) of the paper].—This transmitter utilizes five spot frequencies. Each of these frequencies can, as previously explained, be varied within a few hundred cycles of its nominal setting. The transmitter works into a 700-$\mu\mu$F "T" type aerial giving an aerial current of about 21 to 25 amperes on full power, according to wavelength.

A 2-kW motor-alternator used for modulating is mounted beside the transmitter. The modulation frequency of 700 cycles was selected as giving a distinctive note to the M.C.W. signal, easy and pleasant to read over prolonged periods, and capable of being greatly reduced in strength by the note filters in the receiving room, when multiplexing, as these filters cut off sharply below 900 cycles.

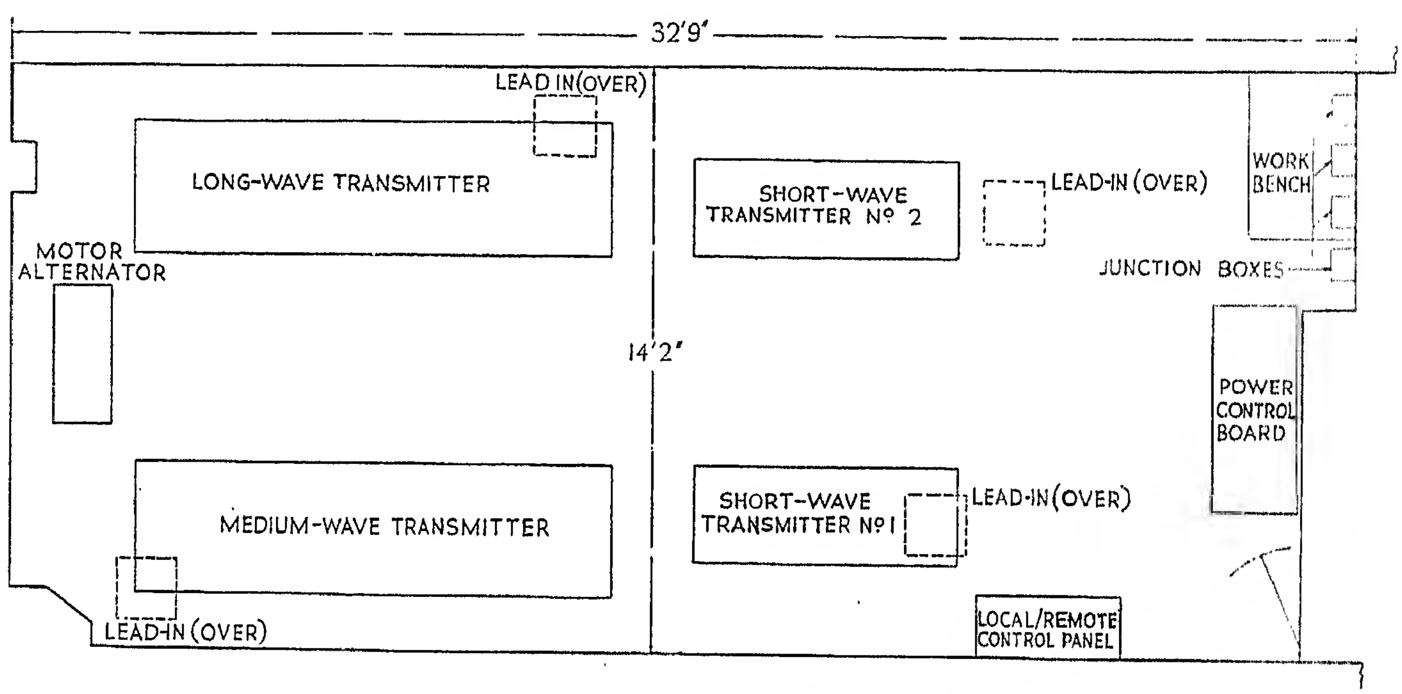


Fig. 23.—Transmitting room of R.M.S. "Queen Mary."

Except for initial switching on of a.c. power to the transmitter, which is performed locally at the switchboard, all control of the transmitter functions (H.T. on-off, power increase or decrease, frequency changing, and C.W. to M.C.W.) is normally carried out remotely from the operating room, duplicate controls being provided in the transmitter itself.

The transmitter is mounted on a special shock-absorbing base comprising two heavy channel-iron plinths, one floating elastically on top of the other and allowing universal motion of the transmitter, to protect the valves and control relays against any vibration which might exist.

(*c*) *A Long-wave Telegraph Transmitter* closely resembling the medium-wave transmitter mentioned above but restricted to C.W. operation, M.C.W. not being permitted on these wavelengths. It utilizes 7 out of the 10 available spot frequencies and works into an "L" type aerial having a capacitance of 2 000 $\mu\mu$F, giving an aerial current of about 25 amperes at full power.

(*d*) *Two Telegraph/Telephone Short-wave Transmitters* [of the type described in Section (3.3)].—These transmitters furnish the two short-wave links of the vessel, one being used normally for communication to Great Britain and the other to the United States. Each has 10 crystal-controlled frequencies between the limits of 3 and 17 megacycles (17 to 100 m.), the frequencies of course being selected so that no mutual interference exists and so that neither the transmitted frequencies nor their harmonics are likely to interfere with reception in the operating room.

Out of the 20 frequencies provided by the two transmitters, 9 are used for telephony and the remaining 11 for telegraphy. Four of the telephone frequencies are the operating frequencies used for communication with London Radio Terminal (via the Post Office receiving station at Baldock) on Transmitter No. 1. The other 5 frequencies are used on Transmitter No. 2 for communicating with the United States via the American Telegraph and Telephone Co.'s station at Forked River.

Similarly, the 11 telegraph frequencies are disposed between the two transmitters so that No. 1 Transmitter is normally used for communication with Great Britain and Europe (mainly through the Post Office station at Burnham), while No. 2 Transmitter normally works to the United States via the Mackay station at Sayville or the R.C.A. station at Chatham.

These frequencies are distributed through the frequency bands between 5 and 17 megacycles, so that a suitable frequency can be chosen according to time of day and the distance to be worked. The arrangement of telegraph frequencies is fairly flexible—i.e. if necessary both transmitters can be used to transmit to the one station, to cope with peak traffic loads—but the telephone frequencies are allocated specifically to a particular shore terminal station and consequently the transmitter for Baldock cannot immediately be transferred to Forked River, and vice versa. Should a breakdown occur, the plug-in tuning units corresponding to two or three of the telephone frequencies in the transmitter affected can be transferred to the other transmitter, from which the same number of tuning units corresponding to the lesser-used frequencies would be withdrawn. The whole change-over can be effected in a few minutes, and the working transmitter would then be used for either east-bound or westbound communication as required, while the defective one was being repaired.

These two transmitters stand upon shock absorbers similar to those used for the medium- and long-wave transmitters.

(*e*) *Auxiliary Control Panel*.—An auxiliary control panel is provided at a small desk near the door to the transmitting room. This panel carries switching arrangements allowing of local keying of any of the four transmitters, monitoring any of the receivers in the operating room, and for putting any of the operating room remote-control arrangements completely out of circuit if required, when overhauling the transmitter concerned.

(4.4). Operating Room.

(4.41). General Arrangement.

The operating room forms the central control point of the entire station, all incoming and outgoing telegraph and telephone traffic being handled here. The layout is shown in Fig. 24. Briefly, the room contains:—

(*a*) Four main operating positions, each with its own set of receivers, telegraph key, and remote-control arrangements for one of the four transmitters, and, in the case of the two "short-wave" positions, the controls for the telephone terminal equipment. Each position is entirely self-contained but can be linked up with the other positions so that if required it can use any transmitter other than that which it normally controls.

(*b*) High-speed positions, auxiliary to the four main operating positions, equipped with tape transmitting and receiving mechanism.

(*c*) Supervisory position provided with monitoring and other arrangements by which the supervisor can perform numerous functions detailed later.

(*d*) Emergency position, providing the battery-driven emergency transmitter and receiver required by law.

Adjacent to the operating room and communicating with it are the passenger office, accepting office, and clerical office, where the business side of traffic handling is performed, and a battery room containing the batteries for the emergency transmitter and receiver. A telephone booth is situated near the passenger office. The operating room and associated rooms are completely enclosed by fireproof bulkheads and doors and in the case of emergency can be isolated against fire, a trap-hatch in the roof of the operating room allowing of escape to the deck above.

Extensive precautions have been taken against interference from the ship's electrical machinery. In addition to the shielding of the receivers themselves, the operating room is lined with copper sheet forming as nearly as possible a closed tank, earthed at one point only to the upper deck. All electrical wiring inside the room is shielded, the shielding being bonded to the copper lining of the room. Every wire entering the room, including lighting, power, telephone, and control lines to the transmitting room, terminates at one or other of several shielded junction boxes, situated in a small compartment immediately external to the copper lining, the main object of this being to insure that noise brought in by wiring can be rapidly located and the offending lines suitably filtered. All lines from the junction boxes to other parts of the ship are also shielded, the shielding being earthed.

As a further precaution against noise, the ship's d.c. mains are normally excluded altogether from the operating room, and all power for lighting this room, operating the receivers and high-speed apparatus, and battery-charging, is derived from the 3-phase a.c. supply provided by the motor-alternator through a 7-kVA 3-phase transformer situated in the same compartment as the junction boxes mentioned above. The primary of this transformer is mesh-connected and the secondary star-connected, with earthed copper shields between the primary and secondary. The star point of the secondary is also earthed, the three outers giving separate single-phase supplies used for (*a*) lighting, (*b*) power supply to receivers, terminal equipment and high-speed equipment, and (*c*) battery-charging. The transformer design precludes the possibility of any noise due to the motor-alternator itself reaching the receivers. A change-over switch external to the room allows the lighting system

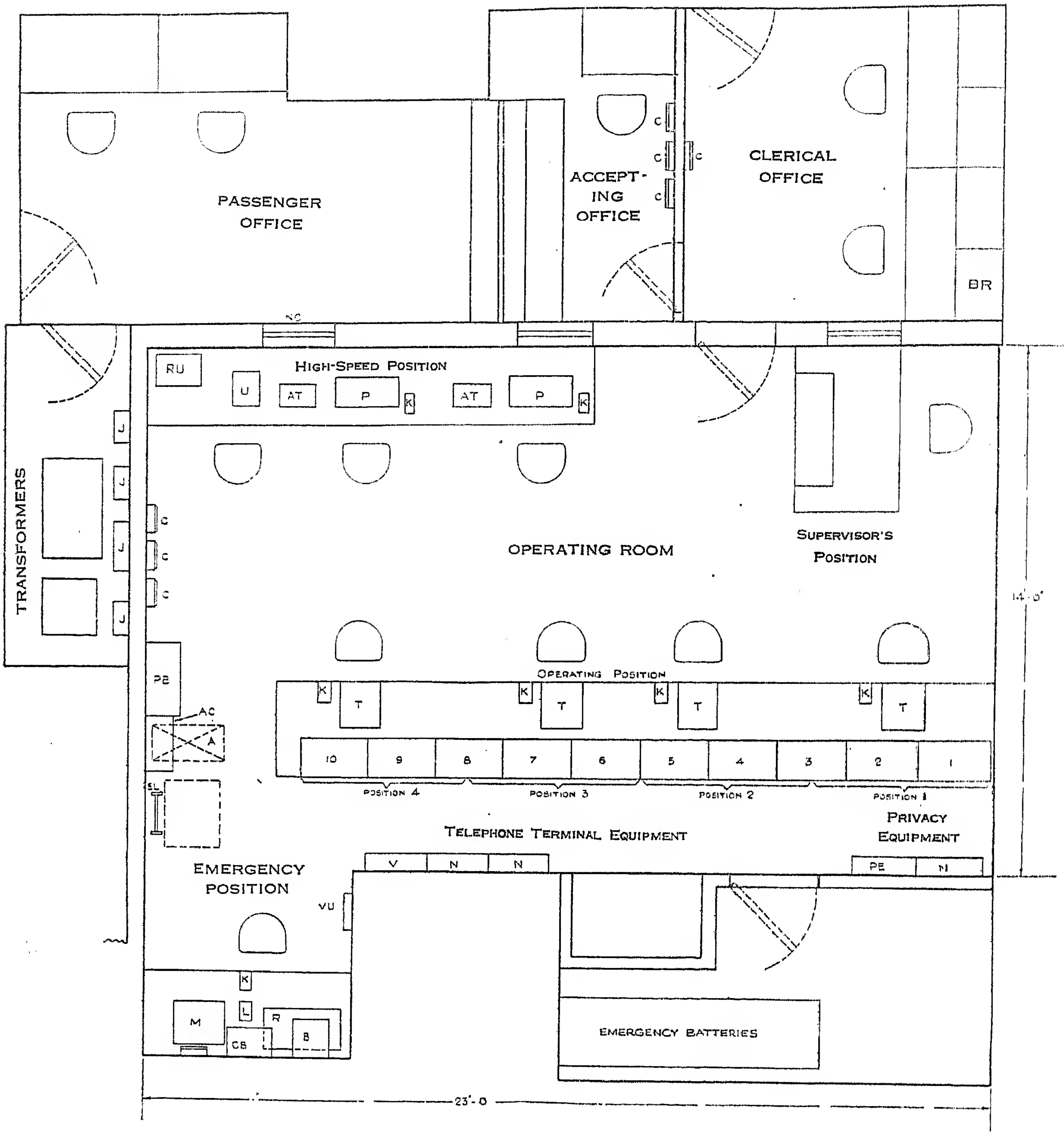


Fig. 24.—Layout of operating room and associated offices on R.M.S. "Queen Mary."

Operating Position.
(T) Typewriter well.
(K) Key.

High-Speed Position.
(P) Perforator.
(AT) High-speed key.
(U) Undulator.
(RU) Rectifier unit.
(K) Key.

Emergency Position.
(M) Transmitter.
(R) Receiver.
(L) Auto alarm key.
(K) Key.
(B) Charging board.
(CB) Battery control board.

General.
(J) Junction boxes.
(C) Clocks (G.M.T.—Ship—N.Y.).
(V) Singing-suppressor equipment.
(VU) Singing-suppressor mains unit.
(N) Delay networks.
(PE) Privacy equipment.
(PB) Power board.
(AC) Aerial connector box.
(NC) Night counter.
(A) Aerial lead-in.
(EL) Escape ladder.
(BR) High-fidelity broadcast receiver.

to be transferred to the ship's mains if required, while a second change-over switch allows of an alternative source of a.c. supply for the receivers from a small motor-alternator used for other services on the ship.

Further precautions against noise interference include the fitting of noise suppressors to the four passenger lift motors just outside the receiving room, and to some 200 fan motors ranging up to 10 h.p. on the upper decks, together with the running in earthed conduit of all cables on the upper decks within 200 ft. of the receiving aerials.

deep, standing at the back of the operating table and facing the operators. Ten such cabinets in all are provided, two to each operating position, plus an extra cabinet between positions 1 and 2 (the short-wave telegraph/telephone positions) and another between positions 3 and 4 (the medium- and long-wave telegraph positions), these additional cabinets containing apparatus common to the positions on either side. The 10 cabinets are bolted together side by side, and are supported by special shock-absorbers to guard the components against vibration. Doors at the back of each cabinet give access

OPERATING POSITION 1 — OPERATING POSITION 2 *

1	2	3	4	5
Mains unit and spare tuning coils	Mains unit and spare tuning coils	Mains unit and spare tuning coils	Mains unit and spare tuning coils	Mains unit and spare tuning coils
S.W. preselector and noise filter	S.W. preselector and noise filter	M.W. preselector	S.W. preselector and noise filter	S.W. preselector and noise filter
S.W. receiver No. 1	S.W. receiver No. 2	M.W. receiver No. 1	S.W. receiver No. 3	S.W. receiver No. 4
Dummy panel	Trans. control unit (S.W.)	Channel indicator panel	Trans. control unit (S.W.)	Dummy panel
4-wire term panel		V.O.D.A.S. control unit		4-wire term. panel
Control panel				Control panel

* OPERATING POSITION 3 — OPERATING POSITION 4

6	7	8	9	10
Mains unit and spare tuning coils	Mains unit and spare tuning coils	Filter panel	M.W. preselector	Mains unit
		Filter panel		
Dummy panel	Dummy panel	L.W. preselector	M.W. receiver (spare)	Mains unit
Dummy panel	Dummy panel	L.W. receiver (spare)	M.W. preselector	L.W. preselector
L.W. preselector	M.W. preselector	Trans. control unit (M.W.)	M.W. receiver No. 3	L.W. receiver No. 2
L.W. receiver No. 1	M.W. receiver No. 2	Trans control unit (L.W.)	Control panel	Note filter
Control panel	Note filter			

Fig. 25.—General arrangement of operating positions on R.M.S. "Queen Mary."

(4.42). Operating Positions.

The four operating positions are situated at a single bench about 20 ft. long and provided with a typewriter well at each position. All telegraphic reception at low speeds (up to 40 words per minute) is carried out aurally, the message being typed out on to the appropriate form by the operator. At the side of each typewriter well is a morse key for hand transmission.

All receivers, control units, telephone terminal control equipment, and operators' key panels, are of the rack-mounting type and are mounted in a set of steel cabinets each measuring 3 ft. 4 in. high by 22 in. wide by 12 in.

for changing valves, etc. The special construction of the panels, known as the "depressed panel system," allows of any repairs being readily carried out after removing the front panels of the cabinets, which are simply cover-plates for the wiring.

Fig. 25 shows the general arrangement of the panels in the cabinets, from which it will be seen that those requiring constant handling by the operators are in the lower parts, while those requiring little or no handling (such as power-supply units, etc.) are in the upper parts. All controls in normal use for any one position are thus within easy reach of the operator. It will be seen that

each operating position contains two receivers together with their preselectors, power-supply units, and note filters, the remote-control unit for one transmitter, and a key and lamp panel. The last-named enables the operator to transfer his morse key from the normal position (keying his own transmitter) to key any of the other three transmitters, while four green and four red lamps at each panel indicate the state of each circuit (i.e. line engaged, line required, line clear for keying); in addition, each key panel allows the operator to transfer his keying line to one of the high-speed positions. This key-panel arrangement greatly adds to the flexibility of the station.

Positions Nos. 1 and 2 are identical, each containing a short-wave telegraph/telephone receiver (described in Section 3.5), the remote control unit for one of the short-wave transmitters, the telephone terminal equipment for one link, and other units as mentioned above. A medium long-wave telegraph receiver (the medium-wave receiver of Section 3.6) is mounted between these two positions, in case either position is required as an additional long-wave telegraph channel. This equipment provides all that is necessary for normal telegraph and telephone communication. Between the two positions is the additional telephone terminal equipment allowing either telephone circuit to be put on a "full singing suppressor" basis should communication conditions demand it, the normal condition being only "half singing suppressor." A spare short-wave receiver is also mounted at each of these positions; this is constantly in circuit and is available for immediate use in the event of a valve or other failure in either receiver.

The two privacy equipments, additional singing-suppressor equipment including a delay network, together with their associated power supply rectifiers, are mounted in telephone-type racks bolted to the bulkhead behind the receivers. These are entirely controlled from the two short-wave operating positions and can be cut in or out of circuit as required.

The two short-wave positions, for telephony, normally connect through 2-wire extensions to the ship's telephone switchboard which connects to the 500 cabin staterooms equipped with telephones and to 2-wire phone booths in various parts of the ship, as well as to the ship's official services. In addition, a number of 4-wire extensions are taken to certain of the principal staterooms, through a special 2-wire to 4-wire sub-switchboard at the ship's exchange, to allow of 4-wire working when desirable. In the case of these staterooms, when 4-wire communication is necessary the operator at the ship's exchange disconnects the subscriber from the 2-wire central exchange and connects him direct to the radio terminal equipment on a 4-wire basis. A 4-wire telephone is also provided in a telephone booth near the radio accepting office and is connected directly to the terminal equipment.

Operating positions Nos. 3 and 4 are somewhat simpler, handling only telegraph communication. The general arrangement is somewhat similar to that of positions 1 and 2, except that the transmitter remote controls are situated in the cabinet between the two positions. This allows an operator at either position to control either the medium-wave or long-wave transmitters. Each of these positions carries a medium-wave receiver (500–3 000 m.) and a long-wave receiver (1 800–20 000 m.). In addition, a spare receiver is carried between positions 3 and 4, for use in the event of breakdown of one of the other receivers.

(4.43). High-speed Position.

Two high-speed tape transmitting keys, together with their associated perforators and a morse undulator, are mounted on a separate table in the operating room. The driving motors of all high-speed apparatus are of the inductor type to avoid commutator noise. Each of the high-speed keys can be connected to operate any one of the four radio transmitters, and can be controlled either locally or from the operating positions.

The tape perforators are of the electrically-operated typewriter pattern, and feed either directly into the auto transmitting key or on to a roller, according as to whether it is desired to transmit the message immediately, or to reserve it for later transmission at high speeds, the latter method being used mostly for letter telegram services.

The morse undulator is operated from any one of the receivers on short or long waves as required (usually the former) through a detector-amplifier having manual and automatic volume controls. The use of two A.V.C.'s (one in the receiver) in cascade results in great stability of operating signal strength. The tape from the undulator is drawn by an electric winder on a slotted runner over a typewriter, and is either transcribed by an operator as it comes out of the inker (in the case of ordinary telegrams) or rolled up for later translation (in the case of Press messages for the ship's newspaper).

The undulator also serves the useful purpose of checking the keying of any of the transmitters, or of either of the automatic keys, for which purpose it is used at regular intervals.

Satisfactory transmission and reception of messages at speeds of up to 80 words per minute have been carried out with the above apparatus.

(4.44). Supervisory Position.

The supervisor sits at a desk overlooking the rest of the operating positions, his duties being to route accepted telegrams to the proper operating position for transmission, to monitor any of the circuits if required, to keep an additional loud-speaker listening watch on the 600-m. wave and on three other circuits, and to perform various circuit-switching duties as described below.

In front of the supervisor is a cabinet bearing a panel equipped with four loud-speakers and a number of telephone-type jacks. Each loud-speaker can be switched to either of two receivers at operating positions Nos. 1, 2, 3, or 4, respectively, and is provided with its own volume control. The loud-speakers are normally connected to the receivers not being used at the moment for traffic working; one of these receivers is always tuned to 600 m. (the international distress wavelength); a second is tuned to 2 100 m. (the international "long" wave used for establishing communication); the other two are normally set to cover two of the principal coast stations during periods when they are not being worked. The maintenance of this auxiliary listening watch ensures

the minimum of delay in answering calls from other stations.

A row of jacks is mounted along the panel below the loud-speakers. Four of these are in parallel with the loud-speakers and allow the output from any receiver to be connected through to lines leading to the transmitting room, for monitoring and testing purposes. Two other jacks connect to the telephone terminal equipments, and allow of the latter being connected through a third jack to the ship's public address equipment or (as in the case of the maiden voyage) to high-quality broadcasting control equipment. In this case the terminal equipment is simply used as a switching link, being otherwise entirely out of circuit and so allowing the passage of the full range of audio frequency required for broadcasting (about 9 kc. as against 3 kc. for ordinary telephony). Other jacks are used for connecting a special high-fidelity broadcast receiver, situated in the clerical office adjacent to the operating room, through to the ship's re-diffusion system, for broadcast entertainment in any of the public rooms.

Special provision is made to give the supervisor direct telephone communication with the navigating bridge and with the transmitter room.

(4.45). Emergency Position.

The emergency position requires little description. It resembles the normal equipment of an ordinary cargo ship and comprises (1) an I.C.W. transmitter of the type referred to in Section (2.2), having three "spot" wavelengths of 600, 705, and 800 m., and delivering some 4 amperes to the emergency aerial, and (2) a 5-valve receiver covering a waveband of 110–2 000 m. The transmitter is operated through a motor-alternator from a 120-volt emergency battery which also provides H.T. for the receiver. The receiver filaments are supplied from a 24-volt battery, which can also be used in the very last resort to operate the transmitting motor-alternator, which is double-wound for 120 and 24 volts input. The batteries are charged from the a.c. supply through a dry rectifier.

(4.5). Aerial System.

In designing the aerial system, the principal points borne in mind were that (*a*) both the transmitting and receiving aerials should have the maximum possible efficiency, and (*b*) the transmitters should interfere as little as possible with reception. These conflicting requirements are difficult to reconcile on a small ship, but fortunately the great size of the "Queen Mary," allowing of comparatively wide separation between the transmitting and receiving points, materially assisted matters.

Fig. 22 illustrates the general aerial arrangement finally adopted. It will be seen that, with the exception of the long-wave aerial, the transmitting aerials are kept to the after part of the ship and the receiving aerials between the first and second funnels, over the operating room.

The medium- and long-wave transmitting aerials were the easiest to arrange, the requirements being that they should be as high as possible and should have large capacity so as to insure low working voltage and reduce any tendency to brush discharge. Accordingly, twin-wire aerials were provided in both cases. These are suspended between spars at the foremast and mainmast heads, the top spans of the one being shackled to those of the other through insulator chains. The medium-wave aerial is of the "T" type, with top span 150 ft. long and a downlead 80 ft. long dropped almost vertically to a steel "trunk" (or protective conduit) leading to the transmitter room below. The long-wave aerial is of the inverted "L" type, with its down-lead at the after end leading to another trunk over the transmitting room.

The two short-wave transmitting aerials are of the inverted "V" type, giving an appreciable directive effect. That for one transmitter comprises two inverted V's in parallel, the apices being suspended one from each end of the mainmast spar, the far end of each V being taken aft to the docking bridge and splayed out to the sides of the ship. The other aerial similarly consists of two wires, the apices of the V's in this case being suspended one from each side of No. 3 funnel. A number of tests were carried out during the construction of these aerials, to determine the best lengths and angles of suspension for the legs of the V, both by field-strength measurements on a launch cruising at various distances from the ship, and by simultaneous measurements taken by a number of observation stations in different parts of the world during the trials, with the ship swung at various angles. For the first aerial mentioned above, the following gains relative to a half-wave vertical aerial were observed in the fore-and-aft direction:—

Frequency Mc.	Gain db.
4	0
8	5
13	8
17	6

The major lobe of transmission was approximately 60° wide at 17 megacycles, gradually widening until there was practically uniform coverage at 4 megacycles. It is interesting to note that preliminary tests, using only a single-wire V suspended on one side of the ship, showed a displacement of the major lobe by some 20° from the fore-and-aft line of the ship; this was corrected by adding the second wire. The other aerial has slightly less directivity, but is still markedly superior to a plain vertical aerial.

The results shown above are in accordance with requirements; during the greater part of the voyage, when the higher frequencies are required, great-circle bearings between the ship and the shore stations in this country and the United States respectively are within 20° of the fore-and-aft line of the ship, and the directive effect is therefore most useful. When the ship is nearing land and requires the 4-megacycle transmission, the great-circle bearing from the ship tends to alter considerably and therefore non-directive transmission is preferable.

Four short-wave horizontal-dipole receiving aerials are fitted, known as the 4-, 8-, 13-, and 17-megacycle aerials respectively, though the actual frequency response of each extends considerably on either side of the nominal frequency. The 8- and 13-megacycle aerials, being the most used, are double-dipoles to increase the frequency coverage.

From each of these aerials a balanced open-wire

transmission line runs down to the top of a trunk above the operating room, and thence through impedance-matching transformers and concentric transmission lines to a switching panel equipped with screened jacks and patch cords, from which in turn concentric cables run to the four short-wave receivers. Any aerial may be connected to any receiver at the switching panel. The use of concentric transmission line is very advantageous in eliminating local interference.

For medium- and long-wave reception two aerials are provided. One of these is of the inverted "L" pattern, suspended between the first and second funnels, and can be switched over to the emergency position in the operating room for use as emergency transmitting and receiving aerial. The other is a relatively short inclined aerial, and is used for reception only, principally for duplexing on long waves and for Press reception. All the medium-wave receivers can be connected to one of the aerials, while all the long-wave receivers can be connected to the other aerial, the connections being made through screened patch cords and jacks and then through a concentric transmission line and rejector circuit. The rejector serves to cut down to a safe value the high voltages induced by the long-wave transmitting aerial which runs directly above the receiving aerials, any residual interference being eliminated in the receiver preselector circuits as explained in Section (3.6).

Finally, a separate aerial is provided for the reception of broadcast programmes. This aerial is quite short (60 ft. in length) and runs from No. 1 funnel to the receiving aerial trunk, from whence it is fed, through impedance-matching transformers and a rejector unit, to the high-fidelity receiver already mentioned. Broadcast reception suffers no interference from the ship's transmission on either short, medium, or long waves.

(4.6). Performance of Station.

The results obtained under the heavy traffic conditions of her maiden voyage fully justified the elaborate equipment with which R.M.S. "Queen Mary" was fitted. The simultaneous demands made by telegraphy, telephony, and broadcasting, kept the four transmitters and at least four of the receivers in continuous operation for the greater part of the time she was at sea. Without the independent operation of several lines of communication, rapid wave-change, and automatic transmission, it would have been quite impossible to handle the traffic that was presented.

Although the scope of this paper is necessarily restricted to the problems affecting the ship station, it is obvious that in many details these problems are intimately associated with conditions at the shore ends of the circuits, and require for their solution the co-operation of the authorities operating the land stations. The effectiveness with which communication was maintained with the "Queen Mary" on all types of service, constitutes in itself the best testimony to the thoroughness with which such co-operation was provided by the Post Office in Great Britain, and by the A.T. and T. Co., Mackay Radio, and other operating companies in the United States.

The results have shown that in spite of the difficulties peculiar to ship installations of this character, by careful engineering a good approach can be made to the operating efficiency of a large land station, where normally the transmitting and receiving sites are some distance apart, and where space is available for extensive aerial arrays.

ACKNOWLEDGMENTS

The authors desire to acknowledge with gratitude the assistance they have received from the Post Office in connection with information regarding traffic, and from Mr. C. W. Earp, Mr. R. A. Meers, and Mr. R. B. Hoffman, in the preparation of the paper; also to the Cunard White Star, Ltd., International Marine Radio Co., Ltd., Standard Telephones and Cables Ltd., and Kolster-Brandes, Ltd., for permission to publish details of the equipment installed on the "Queen Mary" and other vessels.

DISCUSSION BEFORE THE WIRELESS SECTION, 3RD MARCH, 1937

Colonel A. S. Angwin: Despite the limitations of space, on the transmitting side the equipment, as exemplified in the installation in the "Queen Mary," with its devices for quick changes of wavelength, its power rating, and the systems of directive aerial, has reached a stage of development which places it on a plane comparable with its counterpart, the shore station. Similarly, on the receiving side, the introduction of privacy equipment, and the conversion of the 4-wire to the 2-wire circuit, enabling a traveller to speak from any position on the ship, has placed the traveller very much in the same position as if he were speaking from his own office, with the usual facilities of connection to the telephone exchange. These developments in the larger passenger ships are, I think, remarkable.

I notice that the delay circuits associated with the voice-operated devices on the telephony equipment use electro-mechanical relays. There is an alternative, the thermionic-valve type of delay circuit. There are arguments in favour of each, but there is one outstanding feature of the thermionic voice-operated device—namely the space factor—which I think might have led to its use on board ship; it takes a great deal less space than the alternative which is used in this equipment.

One of the difficulties which still remains, at any rate on this side of the Atlantic, is to provide an efficient service to the ship when near the home port. On the American side that difficulty has been largely overcome by the siting of a special station close down on the shore, which works directly to the ship; and on the English side we rely on the use of the indirect wave from Rugby to maintain communication with a ship in the Channel. There is an opportunity here for exploring the use of ultra-short waves. Many years ago some experiments were made with the "Belgenland" in testing the possible use of ultra-short waves for marine purposes. The results were mainly negative, as the experiments were confined to attempts to discover the possibilities of the use of ultra-short waves over long distances. When transmitting from Southampton to a ship in the Channel, it should be practicable to utilize ultra-short waves from a station situated near Southampton connected to the

local telephone exchange and working directly to the ship, instead of going via Rugby and Baldock into the London trunk exchange. A number of channels could be operated on this way, to meet the demand of passengers during the last few hours of the homeward voyage and the commencement of the outward voyage, when a large number of calls could be put through if expeditiously handled.

There is an analogy to this in the use of medium-short waves in the Puget Sound installation of the American Telephone and Telegraph Co., where direct facilities are provided for operating from boats in the Sound direct into the local telephone exchange. The use of ultra-short waves for a similar purpose seems a possibility. These waves are not yet being used for marine purposes. The whole question of the allocation of frequencies will be reviewed at the next five-yearly international conference, to be held in 1938, and it would seem desirable that, if there is an opening for the use of these very short wavelengths for marine purposes, it should be well explored and the possibilities investigated before the conference.

Mr. F. P. Best: Sir Westcott Abell has pointed out that in the last generation the safety of life at sea has increased fourfold, and he attributes most of this increase to the improvement in the science of wireless communication. Wireless communication at sea is, of course, required for other purposes besides safeguarding life, and modern conditions call for a very complete communication system such as is described in the paper. The installation on the "Queen Mary" shows to what limits those of us who are engaged on marine wireless work can go where multiplex working is desirable and where in fact it has to be provided for the benefit of travellers.

In regard to the question of direction-finding, after several years' experience of both types of direction-finders I consider that on many occasions the ordinary Bellini–Tosi system has advantages, not solely on account of the fact that it can be installed in more awkward conditions and positions than the rotating-frame system but also because there is a fatigue factor. The fatigue caused by using a direction-finder over a period, and especially during windy weather, is generally not so great with the Bellini–Tosi system as with the rotating-frame system. Another slight advantage which has been found with the Bellini–Tosi system is that on occasions the direction-finder frame can be installed on the top of the dummy funnel, which is almost the ideal site for a direction-finder.

The precautions which the authors have taken in the fitting of the "Queen Mary" show that they are alive to the difficulties of high noise level from the electrical machinery of various kinds used on modern ships. In certain cases, especially on ships voyaging in warm climates, the vast numbers of fans which are switched on raise the noise level to an alarming extent, and on occasions we have found that the induction problem is almost the most important one in the fitting of the wireless equipment.

Lieut.-Col. C. G. G. Crawley: On the 1st July, 1936, we reduced the ship–shore rates in this country, the standard rate of 11d. a word, which had always been considered rather high, being reduced to 8d. a word. The Post Office had been hoping to be able to do this for some years, but conditions had not been favourable. I should like to know what the authors' company, and possibly some of the others, think about this reduction in rates. I may say that in the second 6 months of last year the total traffic went up by about 23 per cent, compared with the same period in 1935, and in the same 6 months of 1935 it had risen by about 11 per cent compared with that period in 1934. I know that the general conditions of shipping were improving, and indeed it was largely for this reason that we felt justified in reducing rates, and I think that the reduction was made at the right time.

There has been a large increase, too, in "greetings" traffic at Christmas time; in 1936 this went up by 30 per cent as compared with the previous year, and we in the Post Office ascribe the increase largely to the publicity which was given to the service shortly before Christmas. Curiously enough, this traffic is very popular with trawlers. Wick, our station in the north of Scotland, which communicates extensively with trawlers, carried over 60 000 words of Christmas-greeting traffic. Portishead, which communicates with the most distant ships of all sorts, dealt with 160 000 words of greetings traffic.

There is another aspect of wireless communication with ships at sea which is naturally hardly touched on in this paper, but which we consider the most important of all, and that is the casualty traffic. From October to January inclusive we dealt with 120 casualty cases direct from our stations, and this work occupied about 500 hours. When one coast station is dealing with a ship in distress, all the other coast stations within range are silent. These cases generally occur at night when all such stations in the British Isles are within range of one another, so that those 120 cases meant that all our coast stations, excepting the long-range one at Portishead, were out of action for commercial work for some 500 hours during this period. January, 1937, was, I think, the worst month that we have ever had for these casualty cases; 41 cases were dealt with direct by our stations, occupying 220 hours, whereas in January, 1936, there were only 12 cases occupying 12 hours.

Another subject on which I should like to have the opinions of the communication companies is the question of what they can do to help us to develop on sound lines the radiotelephone service with small ships, and to get rid of the strong interference which is going on at the present time. The number of waves available is not great, and the number of trawlers fitted with radiotelephone facilities increases every day; about 850 of our fishing craft are now fitted with telephony installations. Many of them want to talk at the same time when at sea, and they are apt to get on to unauthorized wavelengths and jam the communication of foreign trawlers and other services. One of the reasons for this is that the sets which the manufacturers were providing until recently were easily adjustable to any wavelength in the international waveband for small ships. I believe efforts are now being made to put out sets which can be adjusted only to the proper wavelengths, but I should welcome the views of the wireless companies on this matter.

The authors mention that recently there has been a tendency to regard the direction-finding apparatus in ships as a navigational instrument for operation by the navigating staff. I hope that this idea will not be carried to an extreme as I think there can be no doubt that the man most capable of getting the best results out of this apparatus is the wireless operator. I understand that already there is a desire on the part of navigating officers to have the speed of transmission of beacons reduced below the present speed of 15 words a minute, which was fixed at that low limit to facilitate the recognition of the call sign of the beacon by inexpert operators. It is obvious, I think, that lowering the speed tends to decrease the efficiency of the receiving apparatus as a direction-finder, though it is equally obvious that it is better to do that than to have a navigating officer taking bearings on a wrong beacon because he cannot read the call sign. As regards taking bearings on ships or stations which are not beacons, the navigating officer cannot, of course, hope to be as expert as the wireless operator.

Mr. H. Bishop: There are one or two points about the waveband table on page 183 which are of interest. From the traffic analysis given in Fig. 1, I see that there has been a decrease in the traffic on the long- and medium-wave bands over the period of the graph, 1925–35. Now the bands of wavelengths are those which were agreed at the Washington Conference in 1927. Since then there have been great increases in the air services and also in broadcasting, and this has resulted in serious congestion in the medium- and long-wave bands, adjoining the ship bands. The marine interests have so far made no sacrifices, in spite of an actual decrease in their traffic. The long-wave band, between 1 875 and 2 727 metres, is used only for passenger traffic. If some small concessions could be made to the other services which are hard-pressed for existence in adjoining wavebands it would, I feel sure, be to the good of all concerned. The paper states that the medium-wave band is mainly used for cargo traffic. Is there not a good deal of passenger traffic on these waves? If so, could it not be moved to the long- and short-wave bands, thus releasing some valuable space for broadcasting which is already trespassing, almost unavoidably, in the marine bands? In the short-wave band between 14 and 50 metres (15 000 kc.) broadcasting is allotted 950 kc., or about 6 per cent. The marine interests have the use of 3 900 kc., or about 26 per cent. Owing to the small width of the bands allotted, congestion in the long-distance broadcasting services is acute.

Col. Crawley's remarks regarding the poor frequency stability of trawler sets explain some of the difficulties of interference-free broadcast reception near the coast. I see no information in the paper about frequency stability of short-wave telegraph sets on cargo vessels.

The authors mention that emergency spark transmitters will eventually disappear, but they do not say what will take their place. On page 194 they compare marine and broadcast receivers, pointing out that the latter are not designed to cover such a wide waveband. This is surely not true in these days of "all-wave" broadcast receivers, which cover a very wide band.

There does not seem to be much information in the paper about the three important points of design which are mentioned early in the paper: easy maintenance, anti-vibration, and difficulties with bad mains. I was hoping that each of these would have been dealt with separately.

The "depressed panel system" is an excellent design. By taking off the front panel one has access to many of the important components, including the valves, and by going round to the back the rest of the equipment is easily available.

The programmes broadcast from the "Queen Mary" during her maiden voyage were most successful, and this success was a testimony to the excellent work which had been put into the design and installation of the wireless equipment. During the voyage we carried out 43 broadcasts, occupying a total transmitting time of $10\frac{1}{2}$ hours. They were relayed not only by the B.B.C. in both home and Empire programmes, but also by the three American broadcasting chains, and the French, Dutch, and Danish services. They were all completely successful. 22 microphone extensions were used, and some 8 000 yards of programme wiring were laid all over the ship. We took a frequency characteristic of the transmitter and aerial in order to see what sort of quality we were going to get. It was flat from below 100 to about 4 000 cycles per sec., a very good performance for a transmitter designed for commercial telephony. This was reflected in the satisfactory quality that was obtained in all the broadcasts. I should like to pay a tribute to the assistance we received at all times from the operating staff on the ship. They were always most helpful, in spite of working under great pressure with new equipment.

Captain W. T. Makeig-Jones: From the naval point of view one of the most interesting parts of the paper is the description of the progress which has been made in fitting ships with wireless. It will be seen from Table 1 that there has been a fairly big increase in the last 6 years, but we are also told, a little farther on in the paper, that only 700 vessels out of 14 800 are fitted with short-wave apparatus. Now, in spite of valve transmitters of increasing power, and also amplifiers with many valves and large amplification, the actual normal working range of a ship not working on short waves has hardly increased at all during the last 30 years. In the early days of the War, working with spark transmitters on 1 000 metres and with crystal reception, the cruisers escorting the Canadian Expeditionary Force would have been very disappointed if they had not got a 2 000-mile range each night; yet the figures given by the authors for present-day ranges are only 1 500 miles for large transmitters and 250 miles for small transmitters. The reason for this is obvious; there has been such a general increase in wireless communication that the noise level has risen. I do not think that the ship herself is responsible for that rise in the noise level; it is mainly due to outside interference, to everyone shouting considerably louder than before to try to transmit the same distance. From a naval point of view, in time of war we have to communicate with all merchant ships, and we shall be very pleased when they speed up the fitting of short-wave wireless installations.

It may be of interest if I say something on the naval

aspect of marine radio. The first point is that it is not a problem of communication between a ship and a shore station, but of communication between large numbers of ships and aeroplanes. The fleet flagship is the controlling authority over all the ships and aeroplanes in a fleet. As such, the design of apparatus required for that ship may be compared to that required for the "Queen Mary" so far as the traffic is concerned. The installation in the "Queen Mary," we are told, had to be designed to deal with a peak load with no delay. Our installations must also be designed for the same purpose. Our peak load commences when contact is made with the enemy by an aeroplane or cruiser, and rises rapidly as more aeroplanes and more cruisers sight more enemy ships, until just before the main fleets sight one another it is probably at its maximum, because, in addition to all the reports coming in, orders are going out at the same time. To carry that traffic with no delay we must have duplex working on several channels.

The necessity for speed may perhaps be visualized if one thinks of two fleets approaching each other, each steaming at 25 knots. If an incident occurs in the enemy's fleet, such as an alteration of speed or course or of the disposition of the ships, the Admiral wants to know it, and our aeroplanes and cruisers have to report it. The message has to be written out, coded, transmitted by wireless, decoded, written out again, and reported to the Admiral, and in every minute which elapses between the occurrence of the incident and the time the report reaches the Admiral's hands the fleets will move nearly a mile nearer to each other.

On the technical side our problems are quite different from those of the commercial world. In the paper the authors mention three difficult problems which have to be faced in all marine wireless: vibration, lack of space, and a bad aerial system. From the naval point of view, vibration is as bad as in any merchant ship; we have high-speed machinery and rough weather to deal with. In addition, our apparatus has to stand up to the very heavy shock effect of gunfire, which affects not only the valves in the transmitters and receivers but also the masts and aerials. With regard to space, everything of value in a ship is placed as far as possible below the water-line, or at least under armour, and the space available under armour is very limited, with the result that our allowance is cut down to the bare minimum. We cannot arrange our transmitters in such a way that they can be examined both from the front and from behind; they have to be fixed against the bulkhead, with the minimum space for a gangway between them. The authors refer to a distance of 400 ft. between receivers and transmitters in the "Queen Mary." In naval practice we are lucky if we get masts 100 ft. apart. In a man-of-war, the masts and funnels must be placed as close together as possible in order to leave as wide an arc as possible clear for the guns. In addition, between the masts we often have the anti-aircraft guns, and we have to leave space overhead to enable these to fire at aeroplanes. The large masses of metal in the vicinity of the feeders and the aerials add to our difficulties. The fact that we have to use a very wide range of frequencies means that we cannot use matched feeders. Finally, the wireless office under armour may be 60 ft. or more from the deck insulator to which the feeder is connected.

I am not going to describe our methods of overcoming these difficulties, but I hope I have said enough to show that the problems which I, as a naval officer, expect my technical experts to solve are not easy.

A point to be borne in mind when considering the terrific volume of traffic handled by the "Queen Mary" on her first voyage is that she was not able to carry out the wireless equivalent of a "full power trial"; she could not run across to America first merely in order to see how the wireless installation worked. The handling of this tremendous volume without a hitch was a matter for sincere congratulation to all concerned.

Mr. M. Reed: I should like to endorse the authors' statement in Section (1.5) with regard to the use of the short-wave band for communications which could be made on the long-wave band. The danger, from a marine wireless point of view, of the continuance of this practice is that it may lead to mobile stations losing the exclusive use of the long-wave band.

With reference to the direction-finder shown in Fig. 2, I would suggest that the indication of the bearing by a number viewed through a window is unsuitable for an instrument which may be used by a navigator, because it makes it difficult for him to visualize the significance of the bearing relative to the ship's head.

I must confess to being a little disappointed with Section (2), which concerns normal ship equipments. The authors correctly point out the difficulties of the designer of wireless installations for ships, but they give no illustrations of the way in which these difficulties have been overcome in practice. After all, as Figs. 4, 5, 6, and 7, show, the difference in electrical design between fixed and mobile stations is very slight, and the only novelty, as a rule, lies in the layout of the mobile stations. A handicap, in addition to those mentioned by the authors, which influences the design of mobile stations is the fact that on the majority of mercantile ships the whole of the ship's installation, which may comprise long- and short-wave transmitters, general-purpose and short-wave receivers, a direction-finder, and an auto-alarm, is under the control of a single operator.

I do not agree with the statement in Section (2.2) that master-oscillator control is essential for low-power short-wave transmitters. It is not difficult, given suitable design, for a single-valve transmitter to satisfy the frequency tolerances given in Table 4. An essential point in the design of a ship's short-wave transmitter is the accuracy with which the operator can set his tuning dial, and the ignoring of this detail may make even the most stable master-oscillator control unsuitable in practice. One great advantage which the single-valve system has over the master-oscillator control is that the former provides the operator with a flexible frequency control, and in a congested area it is possible by slight adjustment of frequency on a low-power transmitter to make a communication which would be impossible on one of the fixed frequencies. To my mind, crystal control and settings on spot wavelengths are unsuitable except on the very largest liners which are able to work on fixed schedules very much like point-to-point stations.

With regard to Section (3) of the paper, it is gratifying to find that the long- and medium-wave receivers supplied for the "Queen Mary" are similar in electrical design to the long- and medium-wave receivers for duplex working on the "Aquitania" and "Berengaria," supplied by the company with which I am associated, and that the general design of the duplex arrangements on the "Queen Mary" is on lines similar to that described in a paper* published after the experience gained on these two ships.

Mr. E. W. Braendle: In Section (1.71) of the paper reference is made to the auto-alarm and it is said that the International Radiotelegraphic Conference at Washington (1927) recognized a signal consisting of twelve 4-sec. dashes separated by 1-sec. intervals, to preface the distress signal proper. It would be interesting to have some details as to the reliability of the apparatus involved, together with the degree of safety factor provided.

With regard to Section (1.8), which deals with aids to navigation, perhaps the authors will let us have some statistics as to the accuracy and reliability of bearings experienced by the navigating staff with direction-finding apparatus, together with the distances over which the bearings can normally be taken.

On pages 208 and 209, mention is made of the methods employed for the prevention of "clipping" of speech when the V.O.D.A.S. equipment is employed. It would be of interest to know whether any difficulty was experienced with the transient period of the build-up of the carrier, i.e. the time taken for the carrier to build-up at the instant of switching on—as additive to that of the operating period of the V.O.D.A.S. relays. Further, was any difficulty experienced with what might be termed "explosive" speech, where the first syllable is drowned by a "plop," similar to that due to the switching on or off of the receiver H.T., the effect being to drown completely the first syllable. In certain earlier experimental work with a low-power (100-watt) transmitter, utilizing a rather simplified valve V.O.D.A.S., 4-wire system, some difficulty was experienced first with "clipping" and subsequently with "explosive" speech, such trouble appearing at the receiver end. The trouble was eventually traced, not to the relay trains, but to the actual shape of the operating transient period of the transmitter output. In the first case (i.e. clipping) the transient period was too long and a method was devised to shorten this, which unfortunately resulted in "explosive" speech. The use of a cathode-ray oscillograph quickly demonstrated that the latter trouble was due not so much to the steepness of the transient, but rather to its characteristic shape, and particularly to its leading edge. While the characteristic producing "clipping" was found, as expected, to be due to a prolonged transient period, the "explosive" effect was the result of a transient which can be best expressed as exhibiting the shape of an ideal rectifier characteristic, having extremely sharp bends at both top and bottom, with a very short transient period. The most satisfactory condition was found when the characteristic took on the shape of the normal grid-voltage/anode-current valve characteristic (i.e. with smooth curves top and bottom), while retaining an equally short transient period.

Mr. E. A. Rattue: In Section (1.3) I note the statement that in 1930 there were no British vessels fitted with radiotelephony. It may be of interest to the authors to know that as far back as 1925 a British company equipped a fleet of whalers and a coast station at Stromness, South Georgia (Antarctic), with wireless-telephone apparatus. The transmitters had an aerial power of approximately 50 watts, and good communication was obtained up to distances of 250 miles. By this means the whalers were enabled to keep in touch with each other and the coast station, thus obtaining valuable information on the movements of the whales, which enabled them to conduct their hunting in a more systematic manner than had previously been possible. The results of this experiment amply justified its trial and proved the value of what was at that time a new field of radio communication.

Mr. A. J. Gill: One of the most striking statements in the paper is that the voltage induced into the receiving aerials on the "Queen Mary" is of the order of 1 000 volts. The difficulty of receiving on contiguous wavelengths even when only a few volts are induced is quite enough in many cases, and to endure 1 000 volts seems to me extraordinary and something very difficult to overcome. I think the authors are to be congratulated on being able to work duplex satisfactorily under those conditions. I take it that when the neon tubes are actually discharging they do obtain some interference.

Another interesting point about the installation on the "Queen Mary" is the use of remote control for changing the wavelength. This is of particular interest to me, because 2 or 3 years ago we desired to provide direct control of the transmitters at Portishead from the receiving station at Burnham, and we devised a scheme using dialling as in ordinary automatic telephone equipment over the necessary 22 miles of line. By means of this system we can change the wavelength of the transmitter, the power, and also the system of transmission (either C.W. or modulated C.W.).

With regard to stray noises, I should like to ask whether these are more serious on board ship when they are due to short-wave transmissions than when they are due to long-wave transmissions. One would naturally expect, with approximately equivalent power, to have more trouble from the long wave, because of the higher voltages on the antenna. On the short-wave transmitter, are the crystals thermostatically-controlled or of the low-temperature-coefficient type, or are these refinements unnecessary in view of the wider tolerances applicable? As regards the plugged-in units on the transmitter, is each unit completely screened from other units in the same stage? I notice that in the medium-wave transmitter the switch taps the turns on the tuning coils; is it found necessary to short-circuit the overlapping turns?

Mr. E. C. S. Megaw: There is one small but perhaps important point which the authors have omitted from their survey of progress in Section (1) of the paper, and that is the possible use of ultra-short waves for such purposes as collision prevention and detection of unsuspected obstacles of all kinds. A system of this

* M. Reed: "The Problem of Duplex Telegraphy in the Mercantile Marine Service," *Wireless Engineer*, 1934, vol. 11, p. 122.

sort working on a wavelength of about 17 centimetres has, I believe, been employed on one of the large trans-atlantic liners, and it would be interesting to know the authors' opinion of its possible future.

Mr. E. N. Elford: I am rather surprised to find that the authors advocate valve transmitters for lifeboats; it seems to me that this is one of the few cases where the inherent drawbacks of a spark transmitter are really useful, because a lifeboat wants to make as much fuss and attract as much attention as it possibly can, and I do not think that a valve transmitter can ever compete with a spark transmitter from that point of view.

I should like to ask whether, in the case of the "Queen Mary," it has been found possible to ensure that the accuracy of the direction-finder is completely unaffected by the large number of aerials on the ship. If this is so, I think it is rather a remarkable achievement.

I should like to ask what order of quadrantal error is found on a ship of the size of the "Queen Mary," and also what is the procedure adopted for watch-keeping as required by the Safety of Life at Sea Regulations.

Mr. J. A. Smale: Fig. 1 is stated to represent the record of the ship-and-shore radio traffic handled by the Post Office for the years 1925–1936 inclusive; it would be interesting if the authors could give us figures for the growth of traffic collected by the operating companies on the ships rather than by the British Post Office. It is not that one supposes that the figures given by the Post Office are in any way fictitious, but there is an important point involved here. During the years of trade depression the traffic is falling away, and I think that the recovery of traffic takes place in the curve before the recovery of trade. In 1933 the traffic starts to grow very rapidly, in almost exactly the same way as the short-wave traffic; in fact, the two curves are almost parallel. This rather indicates that the growth of traffic is entirely due to the use of short-wave communication on ships. I should like to suggest, therefore, that this is not really new traffic, but traffic taken away from the long-distance cable and wireless operating companies and transmitted directly to the ships by wireless from the British Post Office stations, with perhaps an improvement in service.

I should like to mention one form of communication —that with the bottom of the ocean—which is not referred to in the paper. Is there a depth sounder on board the "Queen Mary"?

Mr. C. E. Strong: The story of marine radio communication is one in which the manipulation of knobs and the adjustment of the cat's whisker have played a very prominent part. Operators have had to be not only good telegraphists but also, so to speak, good radio amateurs, and good fighters too, able to capture a channel and hold it for 5 minutes or so against half the world. The ether was their hunting-ground, and there, it appears, they played a "catch as catch can" game over several valuable blocks of frequency allocation. It is comforting to think that the "Queen Mary" may exemplify a tendency towards making use where possible of definitely-assigned channels and preset operation of transmitters. The operators are asked to handle traffic over an adequate number of assigned channels, and no temptation is put in their way—in the shape of tuning dials—to try their luck outside those channels. It is obvious that this is the right idea for large ships like the "Queen Mary," but it is possible also that with modern technique this system of preset operation might be capable of extension to other cases. I should like to ask the authors what is their view regarding the future of rigid preset operation in the marine field.

Commander F. G. Loring, and Messrs. W. L. McPherson and W. H. McAllister (*in reply*): Some speakers have commented on the absence of positive information as to how the difficulties of vibration, etc., are overcome in the normal ship equipment. This is not a matter in which any question of principle is involved, and all that could have been done would have been to include in the paper details of particular mechanical arrangements including shock absorbers, etc., a course which considerations of space and relative importance did not appear to justify.

Col. Angwin comments that the use of electro-mechanical relays involves the use of delay networks occupying a considerable amount of space, and suggests that space might have been saved by adopting the valve type of delay circuit. While it is quite true that recourse to valve devices rather than mechanical relays might have reduced the number of delay networks required, yet it must be pointed out that delay networks improve the performance of both valve and relay circuits, and it is questionable whether the same overall efficiency could have been obtained in the operation of the "Queen Mary" equipment had any reduction been made in the delay network system even with the use of valve relays. Since immediate operating efficiency was a prime necessity, it can easily be understood that, in view of the very limited time which would be available for testing, the manufacturers preferred to supply an equipment based on a technique with which they were well familiar rather than turn to a technique whose adoption in this particular case might have been accompanied by initial difficulties.

We are very glad to note Col. Angwin's observations on the use of ultra-short waves, for the experiences of the last four or five years indicate that there is still a large and unexplored field for the exploitation of waves below 10 metres, right down to the micro-ray wave-lengths of only a few centimetres. Owing to the constantly increasing demand made upon those frequencies already allocated, a demand which is most pronounced on the higher frequencies, relief is certain to be sought in the ultra-short-wave band. The fact that this band is not yet in general use for marine purposes seems to render it desirable that definite allocations should be made internationally for those marine purposes for which their application may be applicable. Short-distance communication of the type instanced by Col. Angwin, certain types of radio beacons, and anti-fog devices against collisions at sea, offer examples of possible uses.

We note with interest Mr. Best's remarks on the subject of noise level from electrical machinery, and we can endorse his opinion that this problem is one of the most important to be solved. That it can present some difficulty may be gauged by a comparison with broadcast reception, where the elimination of extraneous noise sources is a vital necessity. For satisfactory broadcast reception, a received signal field of the order of 1 *millivolt*

per metre is considered to be the normal requirement, and a signal/noise ratio of some 40 db. is recommended as a minimum.* In marine communications, field strengths as low as 0·1 *microvolt* per metre are quite common, i.e. satisfactory reception is required with a signal some 80 db. below that considered desirable for broadcasting. Add to this the fact that in a large liner the receiving station is virtually immersed in noise-producing machinery, and it will be appreciated that the most elaborate precautions possible are necessary. In this respect the "Queen Mary," being a new ship, afforded more than the usual facilities for providing such precautions.

With regard to the question of fixed-loop direction-finders versus rotating-loop types, there is undoubtedly much to be said on both sides of the question. The subject of "fatigue" is interesting, but we think that this is largely counterbalanced by the very sharp minima usually given by rotating loops, permitting an accurate bearing to be obtained with a single swing. Against this the fixed loop possesses the advantage of greater flexibility of location; in addition, it permits use of a simple electrical system of quadrantal-error compensation which is easier to adjust though often less accurate than the mechanical compensator usually used in rotating loop systems. A point about the fixed loop which to our minds constitutes a slight weakness is the necessity for having the two loop circuits in perfect condition at all times. Should one circuit develop a defect due to a high-resistance joint, or leakage in the low-capacitance paper-cored cable, or unequal capacitance to earth due, for example, to the cable becoming kinked, bearing errors are introduced which, in the worst cases, might be as high as 90°. With the rotating loop, on the other hand, a defect in connections between loop and receiver would affect only the strength of signals and should not introduce bearing errors.

Col. Crawley's remarks on traffic furnish a useful and interesting addition to the statistics given in the paper. We do not feel ourselves to be in a position to make any useful statement as to the effect which the recent reduction in rates has had on the increase of traffic; this can only be judged by an intensive examination of traffic records from all sources. It should be noted, however, that the decrease of rates only dates from August, 1936, whereas the remarkable increase of traffic shown in Fig. 1 of the paper dates from January, 1934, and we think that this is some evidence that increased prosperity has at least played its part in the satisfactory results obtained.

Col. Crawley also refers to the serious interference now experienced in the small ships' radiotelephony wave band. The solution of this question involves two very difficult problems. One of these is the cost of modification of some 900 existing equipments from easily variable adjustments to "spot" wavelengths, and the other, an even greater one, is the actual organization and control of the communication, bearing in mind that a very large proportion of the users are persons holding the simple radiotelephone certificate, who think of radiotelephony in terms of the individual channel of the inland telephone service to which they are accustomed.

* Report No. (R.I.) 3 published by the International Electrotechnical Commission, 1935.

Finally, Col. Crawley remarks on the operation of the radio direction-finder by the navigating staff. We agree with him that under certain conditions the wireless operator is the person most capable of getting the best results. Nevertheless, the tendency we referred to is quite a marked one, and we are of the opinion that the designers of marine radio equipment will in future devote considerable attention to this aspect of its employment.

Replying to Mr. Bishop, no very noticeable change in the traffic on the long and medium wave bands is to be expected. The 50-kc. band available between 110 and 160 kc. carries passenger traffic and there is no material difference between the number of passenger ships in 1927 and in 1937. Wavelengths in the band are allocated by agreement between the principal maritime countries and at times there is, and always has been, considerable congestion. Relief has, in fact, been already sought, we consider inadvisedly, by the transfer of some of this traffic to the short-wave bands. The 150-kc. band available between 365 kc. and 515 kc. carries the communications of a very large number of ships, and congestion on this band in certain parts of the world is, and always has been, very serious. The amelioration of these conditions is a difficult international problem. The medium-wave band certainly carries some passenger traffic of a local character, but it would not ease the situation to transfer such traffic to either the long-wave band—already congested—or to the short-wave band, already heavily loaded, and where, in addition, it would create world-wide interference. Col. Angwin's reference to ultra-short waves seems to suggest a possible development for future consideration, but much greater experience is necessary before any valid judgment can be formed.

While the marine interests appreciate the difficulties with which broadcasting is faced owing to its continual expansion, it is felt that they undoubtedly have a greater claim than any other service, except aviation, to special consideration, for the reasons given in the opening sentences of the paper.

With regard to Mr. Bishop's comparison of the wave ranges covered by broadcasting and marine receivers, we agree that on the short-wave bands the wave range of a good broadcasting receiver is quite comparable with that required for marine work. On the medium- and long-wave bands, however, broadcasting receivers do not tune higher than 2 000 metres, whereas for marine purposes the receiver must go as high as 20 000 metres.

Capt. Makeig-Jones comments on the fact that ranges do not seem to have increased during the last 30 years, despite the improvements in both transmitters and receivers, and suggests in explanation that the general noise level has risen. There is little doubt that the great multiplication of radio services all over the world has been accompanied by some rise in the natural noise level, particularly at night, but we are rather doubtful whether this is the whole story. With the more extensive use of electrical apparatus on board ship there has been an increase in local noise. The valve receiver itself, with its attendant power-supply sources, is liable to generate a certain amount of noise, and many will

remember that when valves were first introduced as detectors it was frequently remarked that no valve ever gave such a really quiet background as a good crystal detector. Finally, it is quite possible that the availability of valve amplifiers has led to wireless rooms, in warships at least, being sited and constructed with less regard to wireless conditions, and that the use of long transmission lines often renders the whole receiving system more liable to local interference.

Replying to Mr. Reed, we agree that on a direction-finder an open scale has some advantage over a scale viewed through a window, inasmuch as it facilitates the fitting of some device whereby the bearing relative to the ship's head can be directly indicated, as, for example, by superposing an outline plan of the ship on the direction-finder scale as shown in Fig. 3.

We regret we are not in agreement with Mr. Reed's views on the question of master oscillator control in short-wave transmitters. Primarily the question is rather one of stability than of tolerance. Ships are permitted to work anywhere within their allotted short-wave bands, and under such conditions the international regulations lay down that they must have a total *instability* (i.e. wandering from any wavelength to which they happen to be adjusted) of not worse than 0·1 %. Frequency *tolerance*, which, as explained in the paper, includes accuracy of initial adjustment of the wavelength, applies to very few ships and may therefore be disregarded for the purpose of this discussion.

We agree, then, that a single-valve transmitter can be designed which will comply with the present stability (not tolerance) requirements for ships. But this is not the whole story. An instability of 0·1 % represents, for example, on 24 metres, a frequency variation in excess of $\pm$ 10 kc. That variations of this order can, and do occur, with single-valve transmitters becomes only too obvious if one listens on the ship's short-wave bands, where to-day the majority of transmitters are non-master-oscillator controlled. The results are three-fold: First, owing to the unsteady heterodyne note at the receiving end, the speed of communication is considerably retarded, and one or more repetitions of a single message are common practice; secondly, mutual interference between ships is increased; thirdly, uncontrolled single-valve transmitters can be, and usually are, powerful sources of harmonics which may affect not only the mobile ship bands but other bands as well. We are of the opinion that many of the difficulties of communication experienced on the short-wave band are due to the use of uncontrolled transmitters.

Crystal control affords one means of obtaining the necessary stability to provide rapid and easy communication, and, although it incurs perhaps rather too high a rigidity of adjustment for marine purposes, it certainly provides one of the simplest and most reliable means to the end desired—to obtain as nearly as possible absolute stability during a transmission. That other means exist there is no doubt, and possibly the more flexible of these will eventually take the place of crystals for ship work, assuming the present system of permitting ships to work anywhere within the allotted maritime mobile bands continues.

With regard to Mr. Reed's comments on the "Queen Mary" receivers, we are quite in agreement that they are lineal descendants of those used in the "Aquitania" and "Berengaria." They have, however, a very much higher degree of selectivity and sensitivity, derived from advances in both receiving valve technique and in circuit design, and are also designed to withstand much larger induced voltages from the transmitting aerials; all points which experience with the older receivers showed to be vital to really efficient duplexing. No difficulty is experienced in searching with separate receiver and preselector tuning controls, since the preselector is switched out of circuit when searching and is only cut into use when the station is located and duplex working commenced.

Turning to Mr. Braendle's questions, the International "Alarm" signal consists of a series of 12 four-second dashes. The auto-alarms approved by the Board of Trade respond to a series of only three dashes; there is therefore in this respect a factor of safety of four. The type of auto-alarm recently approved by the American authorities must respond to a series of four dashes, and has, therefore, a rather smaller factor of safety with respect to registering a call, but, on the other hand, is less susceptible to false calls.

Stringent tests are laid down by the Board of Trade (Statutory Rules and Orders No. 897, 1932) with which Auto Alarms must comply before approval: briefly, an auto alarm must fulfil the following conditions:—

(*a*) It must respond without readjustment to signals between 585 and 615 metres having an arbitrary signal strength defined as that which would be produced by a transmitter of 45 metre-amperes rating at a distance of 80 miles.

(*b*) It must respond without failure to 100 locally-produced test calls.

(*c*) When installed in an area of intense interference for a continuous test period of 6 weeks, it must not give more than two false calls in any week, and must respond to at least 90 % out of a total of not less than 500 test alarm calls. During this period it is also subjected to varying temperature conditions ranging up to 113° F., which must not in any way affect its operation.

It is interesting to note that an actual auto-alarm tested under condition (*c*) above gave no false calls and registered 99 % of test calls out of a total of 700.

With regard to the direction-finder, its reliability in the hands of a competent navigating officer can hardly be questioned. It is operated to-day by the navigating staff on many important ships. So far as accuracy and range are concerned, it is generally accepted* that radio bearings are accurate:—

(*a*) To within $\pm$ 2° of arc at all ranges over sea by day, and at all ranges up to 40 miles over sea at night.

(*b*) To within $\pm$ 5° of arc up to ranges over sea of about 80–100 miles at night.

Maximum accuracy is obtained at short ranges, and an accuracy of $\pm$ 1° is often possible over sea for ranges of 20 miles at night and 50 miles by day. The expression "at night" means the period between one hour before sunset and one hour after sunrise. Experienced observers can obtain results at much greater ranges.

* *Handbook of the Ratio Direction-Finder*, by Commander F. G. Loring, O.B.E. (Bernard C. Holding, Ltd.).

These are a valuable check on dead reckoning in bad weather.

The "plopping" effect referred to by Mr. Braendle is not noticeable with the "Queen Mary" equipment; this is probably partly due to the switching system on the transmitter and partly to the delay networks in the terminating equipment.

We thank Mr. Rattue for his remarks in connection with whaling-fleet telephony in 1925. There is little doubt that the present-day European trawler telephony services had their origin at least in part in the success of this enterprise carried out with British equipment by a Norwegian fleet in the South Antarctic.

Mr. Gill has raised some interesting points, some of which would have been dealt with more fully in the paper if space had permitted. The question of voltage induced in the receiving aerials (in the case of "Queen Mary," mainly from the long-wave aerial overhead) is a serious one, and it will be realized that a compromise has to be made between receiving efficiency and the arrangement of the receiving aerial to give least pick-up—at least in the case of the long-wave receivers. Should one of the protective discharge tubes across the aerial circuit function, reception in other receivers connected to the same aerial is interfered with, but no interference to receivers operating on other aerials is caused; when the discharge occurs across the output of a preselector no interference to any other receivers is set up. No interference in the short-wave receivers is caused by long-wave transmission, partly due to the balanced short-wave receiving input arrangements and partly to the relative absence of harmonics from the transmissions. The long-wave filters effectively protect their associated receivers from any interference by the short-wave transmitters.

The crystals in the short-wave transmitters are of the low-temperature-coefficient type, ground to an accuracy of 1 part in 10 000, and the frequency tolerances, even on the "shared band" frequencies used by the ship, are hence well within the limits prescribed by regulations. Each plug-in unit of the transmitter is contained within its own shielded case, and hence the various stages of the transmitter are effectively shielded one from the other. In the long-wave transmitter, the "dead-ends" of the tuning coils are short-circuited to prevent excessive voltages across them due to auto-transformer effect.

Mr. Megaw inquires about the application of ultra-short waves for obstacle-detection and collision prevention. We understand that the "Normandie" is fitted with such a device, using a wavelength of 17 cm. to 18 cm. The installation is, however, of an experimental character, and we are not aware that any report on it has so far been published. Some work on this problem has also been done by German investigators, but here again no details are available. The present position appears to be that such work is still very much in the experimental stage, and that the operating technique will have to be considerably simplified before commercial developments can be envisaged.

Mr. Elford considers that lifeboat transmitters should be designed to give the maximum of "fuss." We do not agree that this is essential or even desirable, since the distress signals from the ship's own equipment will have previously attracted attention to the casualty. The questions of range and reliability are, we think, of much greater importance than "fuss," and it is on this score that we advocate the use of valve transmitters, which also offer the further facility of radio-telephony—a facility which might be very useful in the absence of a qualified operator. With regard to Mr. Elford's other questions, the quadrantal error on the "Queen Mary" is 22°; this has been compensated on the scale mechanisms so that the necessary correction is automatically applied. It may be noted here that the magnitude of the quadrantal error is not purely a function of the size of the vessel, as is shown by the case of the "Bremen," where it is understood that the error amounts to 24°. The main wireless equipment of the "Queen Mary" has no effect on the direction-finder; the aerials were so designed that they could be cut in or out of service without altering the calibration, and special precautions were taken to prevent pick-up from the ships' transmitters.

Mr. Smale views the traffic problem as a whole, and suggests that what from the marine aspect is "new" traffic should rather be considered as old traffic diverted to the marine service. While we are not in a position to give figures for the growth of traffic collected by operating companies on ships, there is not the least doubt that Mr. Smale's comment is justified, at least in part, and that the equipment of long-voyage ships with short-wave installations must affect the long-distance cable traffic to some extent, for the reasons given in Section (1.2). With reference to depth-sounders, the "Queen Mary" is equipped with such a device, but since its operation depends not on radio but on acoustic transmission we do not regard it as part of the radio installation.

Mr. Strong raises the question of ships in general using assigned and pre-set wavelengths instead of being permitted to use any wavelength within their prescribed bands. There are so many aspects to the question that a great deal of space would be required to deal adequately with it. To a certain extent the use of pre-set waves does already exist in some wave bands. For example, in the medium-wave band, ships are licensed to use the waves of 600, 705, and 800 metres, plus, if required, one or two others between these limits, and practically all present-day transmitters on these waves are adjusted to give rapid change between these waves only. Again, in the "trawler wave band," by the regional agreement referred to in Section (1.3) of the paper, narrow bands (approaching, in fact, "spot-wave" tuning) are assigned to each country. It will, however, be noted that these cases apply to relatively short-range communications in which the number of ships working within interference range of one another is theoretically relatively small. Even so, interference can be acute—for example, in the English Channel. When we consider short waves, however, difficulties become very much greater. Although in January, 1936, only some 600 ocean-going ships were fitted with short-wave transmitters, it is not unreasonable to suppose that within a few years the number will have greatly increased. As the operating range of these ships is virtually world-wide, and as at any time their communications may be directed to any one of many countries, the difficulty of organizing on a pre-set frequency basis is sufficiently obvious.

From a purely technical standpoint, the use of pre-set short waves undoubtedly permits of much higher overall efficiencies of the transmitters, combined with rapidity of wave-change and reduction of harmonics, and accordingly would be desirable. Our own preference, therefore, would be for the adoption of assigned and pre-set waves in these bands, provided that a workable arrangement which would satisfy both administrative and technical requirements could be evolved.

SCOTTISH CENTRE, AT GLASGOW, 13TH APRIL, 1937

Mr. W. J. Cooper: I am interested in the efficiency ratio of the input on the ship to the output on the aerial, for which a value of the order of 10 per cent was mentioned during the reading of the paper. This at first appears to be a very low efficiency, but when it is realized what tremendous distances can be covered by these small transmitters such a value is seen to be a remarkable achievement. Is there any difference between such efficiency values on the low-, medium-, and long-wave transmission systems?

My second question is: Are the conversations scrambled, and, if so, how is this achieved?

Mr. J. Eccles: The authors indicate the necessity for quick changing of the wavelengths. Is this a technical or a commercial necessity, and what is the reason underlying it?

Perhaps the authors could explain the nature of the equipment in use, and the operations required, in order to determine the location and the direction of another calling station.

Mr. Alexander P. Robertson: If one wants to speak to a certain ship at sea does one merely tune to the appropriate wavelength, like selecting a telephone number, and can other ships tune in to that wavelength and receive the messages?

Mr. D. Low: When the S O S signal is sent out automatically, is the position of the sending ship given automatically as well?

Major Herbert Bell: It would be of benefit if the authors would enlarge upon the administrative aspects of marine radio communications. I am interested to find from the paper what a wealth of combined international effort and good will have been required to achieve the results which, in the general interests of mankind, have already been attained. I should be glad to know how successful such international arrangements are in practice, and whether all nations faithfully abide by the rules which have been laid down.

Mr. H. C. Babb: I should be glad if the authors would tell us where the majority of the messages from the large liners are received in this country.

Commander F. G. Loring, and **Messrs. W. L. McPherson** and **W. H. McAllister** (*in reply*): Replying to Mr. Cooper's question regarding the efficiencies of ship's aerials in the various wave bands, the values for these do in fact differ quite widely, and our mention of an efficiency of around 10 % referred to what might be expected with a moderately good ship's aerial on the medium-wave band. On the long-wave bands, the efficiency drops considerably and is more of the order of 1 %, owing to the rapid decrease in radiation resistance with increase in wavelength, and at the same time an increase in loss resistance in the aerial circuit due to the large tuning inductance coils required. Despite this, the attenuation of long waves over long distances is very much less than that on medium waves, so much so that for the same transmitter power three or four times the range might be expected. This fact makes these waves very suitable for communications up to about 1 500 or 2 000 miles. On short waves the efficiencies vary very widely indeed, and depend almost entirely on the design of the aerial. With a badly designed aerial, efficiencies of only a few per cent may be expected, while a well designed aerial may have an efficiency of well over 50 %.

Replying to Mr. Cooper's second question, on the "Queen Mary" speech is scrambled for all normal radiotelephone communications, using the apparatus described in Section (3.7) of the paper. The only exception to this rule is in the case of transmissions intended to be relayed to the general public through a broadcasting system, in which case secrecy is obviously of no moment.

In reply to Mr. Eccles, the necessity for quick wave-change is almost entirely commercial. A practically instantaneous wave-change maintains the continuity of the communication. A delayed wave-change results not only in the loss of this continuity but is often also associated with the necessity for the complete and formal re-establishment of the communication itself.

Referring to Mr. Eccles's second question, it is not usually necessary to determine the location and direction of another station for normal communications, but, if required, this is achieved by means of direction-finding apparatus [see Section (1.8) of the paper].

With reference to the question asked by Mr. Robertson, every ship and land station has its own particular identifying code letters which are used to establish communication on specific wavelengths which are allocated to this purpose by international agreement. Normal communication between ships or between ships and land stations can be intercepted by any person having a suitable receiver, and for this reason all operators or persons having receivers are bound by law to preserve the secrecy of anything which they may overhear. Confidential messages are, of course, usually coded and speech can be rendered unintelligible to the eavesdropper by the use of privacy scrambling equipment as used in the "Queen Mary" and described in Section (3.7) of the paper.

In reply to Mr. Low, the advisability or otherwise of an automatic transmission of her position by a ship in distress is a question to which full consideration has been given at different times. Though such a procedure may at first sight seem both reasonable and desirable, a careful consideration of all that is involved shows it to have important disadvantages and indicates that its adoption would not tend towards increasing the safety of life at sea.

Major Bell inquires as to the administrative aspect of marine radio. It is difficult to give this information in

a form suitable to the purposes of this paper. Of all communication services marine radio is perhaps the most truly international, and this was recognized in 1906 when the first international conference was called by the German administration of the day. The last conference was held at Madrid in 1932, when the representatives of 75 countries appended their signatures to the Convention. The next conference will take place at Cairo in February, 1938. At these conferences the whole service comes under the review of the competent administrative and technical experts—the stations, the operators, the rates, and the procedure—and Major Bell will find the detailed results of these conferences in a Stationery Office publication entitled "General Radiocommunication Regulations annexed to the International Telecommunications Convention, Madrid, 1932."

The difficulty involved in the organization of satisfactory intercommunication between so many stations of so many different nationalities, all desirous of using a common medium—the ether—each to his own best advantage, is obvious, but it can be said without question that the results are in practice very good—even surprisingly so. In all essentials the nations do, in fact, faithfully abide by the rules which have been laid down and which are in many cases the result of much give-and-take on the part of many of them.

Replying to Mr. Babb, the majority of wireless messages from large liners are received at the Post Office Radio Station at Burnham-on-Sea. The corresponding transmitting station is at Portishead. Long-distance telephony is received at Baldock, the transmitting station being at Rugby.

THE EFFICIENT RATING AND DISPOSITION OF SUPPLY APPARATUS ON HIGH-VOLTAGE URBAN SYSTEMS

By J. ECCLES, B.Sc., Associate Member.

[*Paper first received* 23*rd April and in final form* 9*th November*, 1936; *read before the* TRANSMISSION SECTION 13*th January*, *before the* SCOTTISH CENTRE 12*th January, and before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 23*rd February*, 1937.]

SUMMARY

The paper presents a technical approach to the problems of safe and economical control and operation of certain power networks. The initial sections are devoted to a quantitative discussion on circuit-breaker duty and short-circuit phenomena at points of supply and at remote points on the network.

Some effects of interconnected working are indicated. Means for current limitation and alternative methods of control under fault conditions are described.

The design and protection of cable networks are reviewed and the characteristics of transformers briefly discussed. Finally, some comments are offered on the layout of medium-voltage apparatus and on the problem of voltage variation at consumers' terminals.

The discussion is confined to phenomena on urban networks operating at voltages not exceeding 11 kV.

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(1) INTRODUCTION

The electricity supply industry in this country has, during the past decade, been passing through a period of evolutionary changes unparalleled in its previous history. These changes, mainly consequent on the growth of output and the policy of system interconnection, have created technical problems which so transcend their earlier prototypes as to necessitate, in some cases, fresh methods of approach if physically safe, yet reasonably economic, solutions are to be found.

With the ever-increasing range of possible applications of electric power, the industrial and general public are becoming more and more dependent on a continuous supply. Thus, whilst the growth of load accentuates certain problems in the maintenance of continuity, the fact that this load has so permeated our industrial and domestic affairs makes it more than ever incumbent on supply engineers to take all practicable precautions against the possibility of a sustained interruption. Indeed, it may not be too much to suggest that the success or comparative failure of the supply industry to command the lasting confidence of the consuming public will be measured by the ability of technical executives to hold the balance fairly between the quality of the service rendered and its cost.

There are two pre-requisites to a just appreciation of the position: (*a*) Knowledge of the nature and quantitative value of the phenomena to which supply apparatus may be subjected. (*b*) Knowledge of the manner in which such apparatus will react when subjected to these phenomena. These desiderata having been obtained, the way is opened to a consideration of alternative designs and arrangements of apparatus which will provide a system that is physically safe, technically efficient, and economically practicable.

The present paper reviews some of these problems in a general manner, which, it is hoped, may be of interest to those wishing to investigate kindred phenomena on specific systems.

(2) CIRCUIT-BREAKER DUTY

The requirements of an efficient circuit-breaker are that it shall be insulated for the circuit voltage, carry the normal rated current continuously without undue heating, repeatedly make and break all currents up to a specified value, and withstand the mechanical and thermal stresses associated with these currents without distress or dangerous rise in temperature.

The first two requirements, being common to all electrical apparatus, are well understood by switchgear designers, but although in recent years much thought has been directed to the latter two, there still remain aspects which are complex and obscure. In discussing circuit interruption on alternating-current systems it is, strictly speaking, incorrect to state that the circuit breaker interrupts the current. Rather is it that the current ceases to flow at a point of reversal and is prevented from restarting through the inability of the potential difference between the circuit-breaker terminals to break down the dielectric properties of the medium in the gaps between the separating contacts. The restoration of electric strength in gaseous media under pressure proceeds very rapidly when the current has ceased to flow, and hence the potential difference which

is mainly effective in breaking down the gaps is that present across the circuit-breaker terminals during the first few microseconds after the cessation of current. For symmetrical fault current this value depends on the circuit recovery voltage (at power frequency), the power factor of the fault circuit, the inductance and capacitance of the system, and the characteristics of the circuit breaker itself.

Fig. 1(a) shows an elementary circuit of resistance R ohms, inductance L henrys, and capacitance C farads in which an e.m.f. E circulates a current I through a circuit breaker C.B. Fig. 1(b) shows, diagrammatically, the circuit conditions on the opening of C.B. on a symmetrical fault. At the final current-zero the circuit recovery voltage is e, the arc voltage E_{CB}, and there is established a high-frequency transient restriking voltage, the amplitude of which is $(e + E_{CB})$, having a maximum component $(2e + E_{CB})$ tending to re-establish the current.

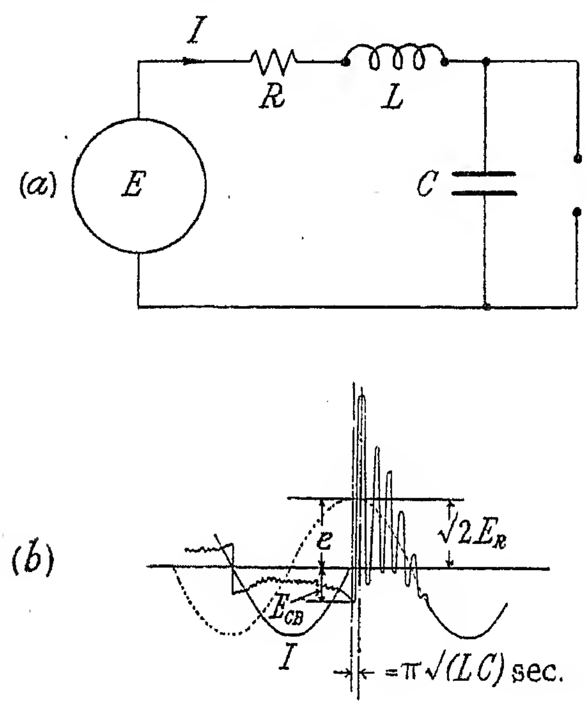

Fig. 1
(a) Elementary circuit.
(b) Restriking voltage.

The frequency of this transient, which is sometimes referred to as the natural frequency of the circuit, is given by

$$f_1 = \frac{1}{2\pi\sqrt{(LC)}}$$

The average rate of change of voltage (in volts per sec.) across the circuit-breaker terminals is

$$2(e + E_{CB})2f_1 = \frac{2(e + E_{CB})}{\pi\sqrt{(LC)}}$$

but, since part of this change is occupied in cancelling out the arc voltage E_{CB}, the effective average rate of rise of the component tending to re-establish the current is $(2e + E_{CB})2f_1$ volts per sec. For any circuit of r.m.s. recovery voltage E_R the value of e at the instant of rupture is $\sqrt{2}E_R \sin\phi$, where ϕ is the power-factor angle of the fault circuit. Thus the effective average rate of rise at the circuit-breaker terminals becomes

$$(2\sqrt{2}E_R \sin\phi + E_{CB})2f_1 \quad . \quad . \quad . \quad . \quad (1)$$

The first term within the brackets in equation (1) is a maximum, for a given value of E_R, when $\cos\phi$ is zero; a fact which illustrates the effect of low power factor on circuit-breaker duty. As will be shown later, the value of E_R is controlled by several variables. It can be shown that on certain 3-phase faults the r.m.s. value of the power-frequency recovery voltage, in the first phase to be interrupted, is 1·5 times the phase-to-neutral recovery voltage (E_{RP}), and that in the two remaining phases is $0{\cdot}866E_{RP}$—a point which has to be borne in mind when testing such circuit breakers on a single-phase circuit. Theoretically, the arc resistance (R), for a given length of arc, might be expected to be inversely proportional to the current flowing (I), and therefore E_{CB}, being the product of I and R, should be independent of I and, in any given circuit breaker, solely proportional to the arc length. In practice, mainly owing to arc cooling in liquid dielectrics towards the end of each current wave, R tends to increase more rapidly than the sinusoidal decrease of I, with two results: (a) E_{CB} increases more rapidly than the length of arc, and (b) the current is suppressed more rapidly than a sine law would demand. The final value of E_{CB} is controlled by the electrostatic capacitance of the system in which the circuit breaker is connected and by the characteristics of the circuit breaker itself, whilst the premature suppression of the current increases the well-known zero pause, which is believed to play an important role in arc extinction.

The value of f_1, expressed in cycles per sec., may vary from 500, for a large cable network supplied by commercial alternators, to 25 000 for an isolated commercial alternator of moderate reactance.

The r.m.s. current in the gap immediately previous to rupture is easily computed when successive current pulsations are of the same time-duration (symmetrical current), but when this is not so there are two disturbing features: (a) Successive pulsations have widely divergent r.m.s. values; and (b) the time position of zero current is not fixed relative to that of the recovery voltage.

Fig. 2(a) shows a substantially asymmetrical current, the alternating component of which is at zero power factor relative to the recovery voltage. The recovery voltage e at successive current-zeros is shown. The current zero following the major pulsation is favourable to arc extinction in that the value of e is low and is decreasing, though unfavourable in that the electric strength of the gap is low owing to the heavy-current pulsation which is just terminating. The converse holds for the current zero following the minor pulsation.

If the alternating component is at unity power factor, these relationships are again changed [Fig. 2(b)], but this is a condition of no practical importance in that a highly resistive fault circuit is postulated wherein the restoration of symmetry would be completed before a normal circuit-breaker could have operated.

The electromagnetic force on the conductors and mechanism of a given circuit-breaker varies as the square of the instantaneous current, and as a completely asymmetrical current may, on a 3-phase circuit, rise to 1·8 times the calculated initial instantaneous value of the symmetrical current of the same circuit, the force is increased to 3·24 times that of the symmetrical case.

The temperature-rise of current-carrying parts under

fault conditions is proportional to the product of the mean square of the current with time, and inversely proportional to the thermal-storage capacity of the conductor. Local to the arc there is a further temperature-rise proportional to arc energy and inversely proportional to the thermal-storage capacity of the affected parts. The bursting pressure on the circuit-breaker enclosure, for a given design, should be proportional to the arc energy, but many inconsistent results have been recorded.

This brief résumé of fundamental conceptions is not intended to be exhaustive, but rather to indicate in outline the complexity of the task with which the circuit-breaker designer is faced. It is recognized, for example, that a system may have more than one natural frequency, and that the manner in which the circuit breaker permits microscopic currents to flow after the final interruption of the main power arc has a profound effect on the rate of rise and maximum value of restriking voltage. Further, the electric strength of the gap is a function of the

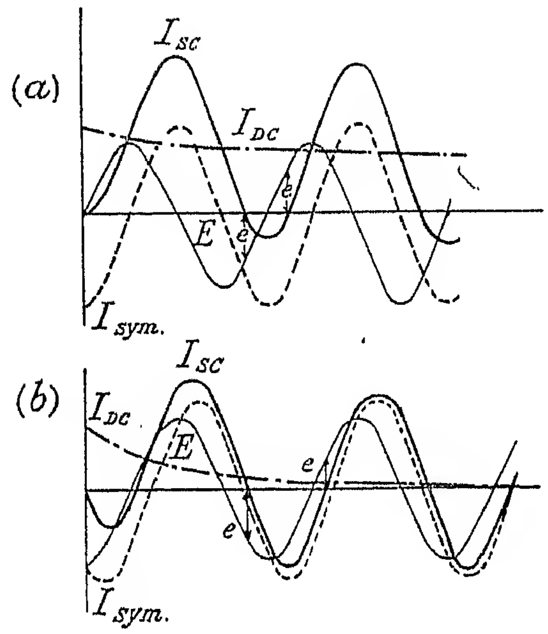

Fig. 2
(a) Asymmetrical fault, zero power factor.
(b) Asymmetrical fault, unity power factor.

diameter of the arc, and of the constitution of the gaseous medium present. With the exception of the first-named, these features vary with the design of switchgear, and are factors of which the supply engineer cannot well take cognizance in a switchgear specification.

(3) SYMMETRICAL SHORT-CIRCUIT CURRENT

The symmetrical short-circuit current, at any time and position on a network, depends on the circuit voltage, the impedance between the energy source and the fault, and the manner in which these quantities vary with time. Since the largest short-circuit currents are associated with faults at or near to sources of energy, it is proposed first to examine these phenomena in some detail and thereafter to deal generally with network faults. In the initial discussion a symmetrical 3-phase fault will be assumed.

When a 3-phase turbo-alternator, excited to produce normal voltage (E) at no load, is suddenly short-circuited at its terminals, the currents in both stator and rotor windings rise to high initial values, and then fall—rapidly at first, but subsequently more gradually—to a relatively small steady value. On the application of the short-circuit, the stator m.m.f. thus changes from zero to a high value, and, acting substantially in opposition to the rotor m.m.f., tends to suppress the main flux. The resultant change in flux induces e.m.f.'s in the stator winding, the rotor winding, the rotor damper winding, and the rotor body, in a sense which tends to produce currents to magnetize the mutual magnetic circuit in a direction contrary to the flux-change. In this way there is developed a large rotor m.m.f. which opposes that of the stator and tends to preserve the *status quo* in respect of the generated e.m.f. (E). The currents induced in damper windings and all other eddy-current paths contribute to this result. The air-gap flux, and hence the generated e.m.f., is but slightly reduced as the stator current increases, and the latter is only limited by the effective impedance of the stator winding. The resistance component (R_a) of this impedance being usually negligibly small, the term " effective reactance " may be substituted in the above statement without introducing serious error. Some authorities have used the term " sub-transient reactance " (X'') in this connection to indicate the quantity in ohms which, divided into the no-load e.m.f. per phase ($E/\sqrt{3}$), gives the r.m.s. value of the initial (zero time) symmetrical short-circuit current. This quantity X'' thus takes into account any diminution in generated e.m.f. and the combined effects of stator and field leakage at the instant when the stator m.m.f. is a maximum. The heavy eddy currents which flow in every path at the surface of the rotor as the stator current rises, reduce field leakage to a minimum, and hence the numerical value of X'' for commercial machines is only slightly greater than the calculated reactance of the stator winding under steady load conditions due to stator leakage-flux only.

On reaching the initial peak, the rate of change of stator m.m.f. falls to zero, and the currents induced in all rotor circuits commence to decay. The current in each rotor path decreases exponentially according to the ratio inductance/resistance (the time-constant) of that path. For the eddy-current paths the time-constant (T'') is usually small, and hence the decay is rapid; whilst for the main rotor field the time-constant (T') is relatively large and the decay less rapid.

With the collapse of the rotor eddy-currents the field leakage increases, and superposed on the reduction in air-gap flux owing to diminishing rotor m.m.f. there is a further reduction owing to this extra leakage. This latter effect may, conveniently and without loss of accuracy, be thought of as an increase in the apparent reactance of the stator winding as the rotor eddies disappear, and the term " transient reactance " (X') has been introduced to satisfy this conception. X' might be defined as the ratio of the no-load e.m.f. per phase to the initial (zero time) symmetrical r.m.s. short-circuit current in a machine whose only rotor circuit is the field winding.

Hahn and Wagner have shown, from test-results over a wide range of turbo-alternators, that the relationship between X' and X'' may be expressed as

$$X' = 2 + 1\cdot 4X'' \quad . \quad . \quad . \quad . \quad (2)$$

where X' and X'' are in the form of percentages at

rated kVA. Test results on British designs agree closely with this relationship.

The decay of the induced rotor m.m.f. is governed by the time-constants of its separate components, and the stator m.m.f. follows closely the same law, if due account is taken of the appropriate reactance at each stage. Should the short-circuit be sustained, the rotor and stator m.m.f.'s thus decrease with time, the mutual flux (and hence the generated e.m.f.) becoming smaller and smaller, until, on returning to its pre-fault value, the rotor m.m.f. remains constant and with it the stator m.m.f. The term "synchronous reactance" (X_0) has been used by some authorities to indicate the ratio of no-load e.m.f. per phase ($E/\sqrt{3}$) to the final steady r.m.s. value of short-circuit current for the same excitation. In order that the value of X_0 may be constant over a wide range of excitation, it is necessary to treat $E/\sqrt{3}$ as

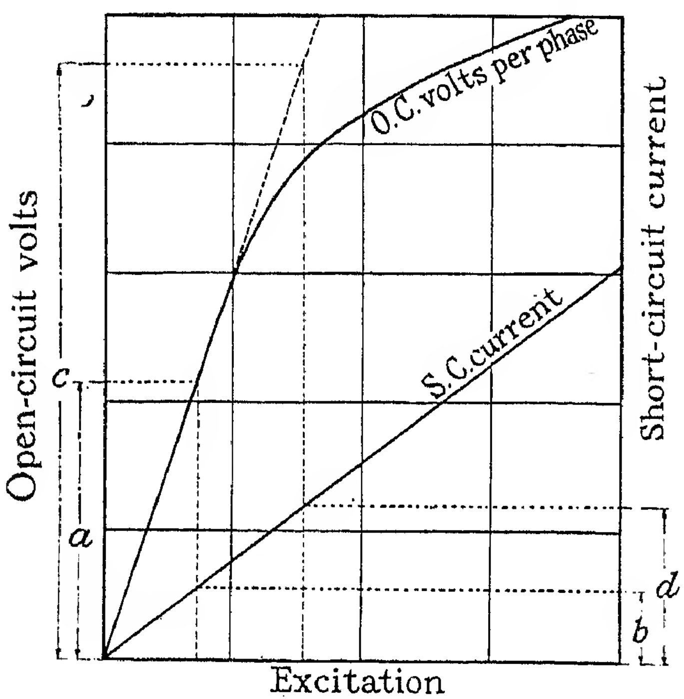

Fig. 3.—Open-circuit and short-circuit characteristics of turbo-alternator.

the air line e.m.f. per phase, and neglect saturation. Thus, in Fig. 3, $X_0 = a/b = c/d$.

As thus defined, X_0 is also useful in determining the transient time-constant T', which has been shown to be related to the open-circuit time-constant (T_0) of the field winding according to the equation

$$T' = T_0\left(\frac{X'}{X_0}\right) \text{ sec.} \quad . \quad . \quad . \quad . \quad (3)$$

Fig. 4 shows typical values of T_0 for modern turbo-alternators from which the value of T' may be deduced, according to equation (3), with sufficient accuracy for application to circuit-breaking problems on 3-phase 50-cycle systems.

The sub-transient time-constant (T'') is not readily calculable, though, in published tests taken over a wide range of turbo-alternators, it has been shown to vary between 0·02 and 0·05 sec., with an average value of 0·035 sec.

In terms of the foregoing constants, the symmetrical r.m.s. short-circuit current (I_t), in amperes, at time t sec. after fault inception, may be determined from the following expression:—

$$I_t = \frac{E}{\sqrt{3}}\left[\left(\frac{1}{X''} - \frac{1}{X'}\right)\epsilon^{-t/T''} + \left(\frac{1}{X'} - \frac{1}{X_0}\right)\epsilon^{-t/T'} + \frac{1}{X_0}\right] \quad (4)$$

where ϵ is the base of Napierian logarithms, and the reactances are expressed in ohms per phase.

It is sometimes more convenient to express I_t as a multiple of the rated output current of the machine, and the reactances as percentage reactances based on the rated output in kVA. Using this nomenclature, equation (4) becomes

$$I_t = 100\left(\frac{1}{X''} - \frac{1}{X'}\right)\epsilon^{-t/T''} + 100\left(\frac{1}{X'} - \frac{1}{X_0}\right)\epsilon^{-t/T'} + \frac{100}{X_0} \quad (4a)$$

Hitherto we have considered a short-circuit on an unloaded machine, whereas, in practice, faults may occur when the alternator is carrying any load within its designed rating. The rigorous calculation of short-circuit current of a loaded machine is somewhat complex, but the following simplified treatment gives results of sufficient accuracy for practical purposes. The method

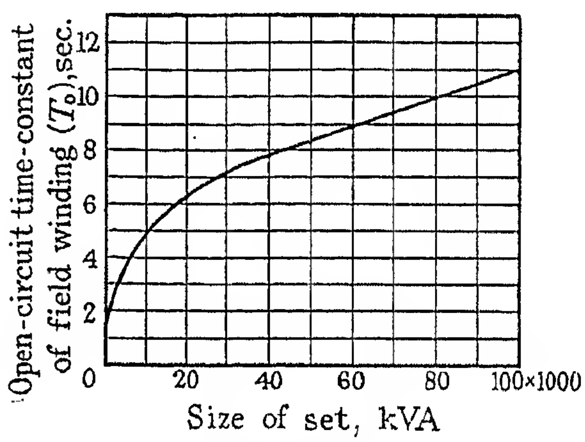

Fig. 4.—Open-circuit time-constants of turbo-alternator field windings.

is to add the reactance drop in the stator winding, due to load current, to the terminal voltage (E_T), in order to arrive at the pre-fault generated e.m.f. The sub-transient and transient reactance-drops are separately computed, and each is used in association with its own component of short-circuit current. Thus $E_{11} = E_T + \sqrt{3}IX'' \sin\phi$ is the sub-transient internal e.m.f., and $E_1 = E_T + \sqrt{3}IX' \sin\phi$ is the transient internal e.m.f.; where I is the load current, and ϕ is the power-factor angle of the load current relative to E_T. The final steady short-circuit current is proportional to the excitation.

When an alternator is supplying commercial load it is the terminal voltage E_T which is measured and is required to remain constant or to vary in a controlled manner, and hence, for this condition, equation (4) may be rewritten in a more useful form as follows; substituting E_T for E,

$$I_t = \frac{E_T}{\sqrt{3}}\left[\left(\frac{K''}{X''} - \frac{K'}{X'}\right)\epsilon^{-t/T''} + \left(\frac{K'}{X'} - \frac{K_0}{X_0}\right)\epsilon^{-t/T'} + \frac{K_0}{X_0}\right] \quad (5)$$

where $$K'' = 1 + \frac{\sqrt{3}IX'' \sin \phi}{E_T}$$

$$K' = 1 + \frac{\sqrt{3}IX' \sin \phi}{E_T}$$

and

$$K_0 = \frac{\text{Excitation at load under consideration}}{\text{Excitation at no-load and terminal voltage } E_T}.$$

Similarly equation (4*a*) may be rewritten:—

$$I_t = 100\left(\frac{K''}{X''} - \frac{K'}{X'}\right)\epsilon^{-t/T''} + 100\left(\frac{K'}{X'} - \frac{K_0}{X_0}\right)\epsilon^{-t/T'} + \frac{100}{X_0}K_0 \quad . \quad (5a)$$

An underlying assumption of both equation (4*a*) and equation (5*a*) is that the pre-fault terminal voltage is the normal voltage of the machine. Should the short-circuit current corresponding to any other terminal voltage be required, equations (4) or (5) may be used and the appropriate voltage inserted. The deviation from normal voltage may have a considerable effect on the value of I_t, particularly on systems in which it is the practice to bring up the busbar voltage with load to compensate for network drop.

In order to estimate the most severe switching condition in such cases, E_T should be taken as the maximum busbar voltage, and the excitation corresponding to the rated output of the machine at this voltage and the design power factor be used in computing K_0.

(4) ASYMMETRICAL SHORT-CIRCUIT CURRENT

The condition to produce a symmetrical current on a single-phase circuit is that the short-circuit should occur at a point on the voltage wave when, according to the circuit constants (resistance, reactance, and capacitance), the current wave would naturally be passing through zero; and the degree of asymmetry, in any given case, is proportional to the sine of the time-phase angle by which the voltage wave is displaced from this point at the instant of fault inception. Owing to the time-phase displacement of the voltages in a 3-phase circuit, it is impossible, with balanced impedances, to choose an instant for fault inception which will produce a symmetrical current in all three phases. Theoretically, the value at zero time of a completely asymmetrical short-circuit current is twice the zero-time peak value of the symmetrical short-circuit current of the same circuit. Actually, the short-circuit current on an unloaded machine at zero time is zero, and the first peak value of a completely asymmetrical wave occurs after a time-interval equal to 1 half-cycle, at the end of which interval, in the case of an unloaded 3-phase alternator short-circuited at its terminals, the decrements have operated to reduce the peak value to about 90 per cent of its theoretical maximum. For these conditions, the maximum effective asymmetrical current is therefore $2 \times 0 \cdot 9 \, (= 1 \cdot 8)$ times the theoretical maximum peak value of the symmetrical current. The rate at which symmetry is restored depends on the ratio inductance/resistance, or the time-constant (T'''), of the fault circuit. For short-circuits at the machine terminals, the inductance to be used in computing T''' is that corresponding to the sub-transient reactance of the stator winding, and the resistance is the d.c. resistance at the prevailing winding temperature. Hence

$$T''' = \frac{X''}{2\pi f R_a} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where f is the frequency of supply.

For short-circuits at the terminals of a loaded machine, the theoretical maximum asymmetrical peak is equal to the maximum symmetrical peak plus the vector difference between the symmetrical peak and the peak value of the load current. These relationships are shown in Fig. 5.

An asymmetrical wave may be regarded as comprising a symmetrical alternating component and a direct-current component. One effect of the d.c. component in alternator short-circuits is to produce a stator m.m.f. stationary in space, and therefore rotating at synchronous speed relative to the rotor winding, thus inducing a synchronous e.m.f. in this winding which produces a corresponding ripple in the rotor current.

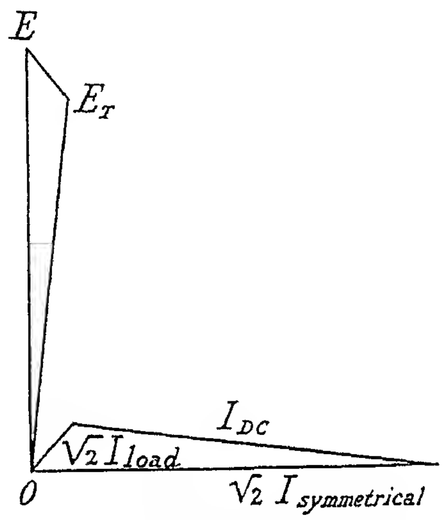

Fig. 5.—Method of determining asymmetrical component on loaded machine.

(5) ANALYSIS OF SHORT-CIRCUIT RECORDS

Fig. 6 is a copy of an oscillographic record of a 3-phase short-circuit on a 10 500-volt 40 000-kVA 50-cycle alternator. The rapid rise and slow decay of stator and rotor current are well shown, as is also the synchronous ripple in the field current due to the asymmetry. An interesting point brought out by the stator-current record of phase 2 is that, owing to the more rapid initial decay of the alternating-current component than the direct-current component, the resultant current does not pass through zero until several cycles have elapsed. That phases 2 and 3 both show almost complete asymmetry is due to the non-simultaneous application of the short-circuit on all three phases.

Fig. 7, curve (*a*), shows the r.m.s. current in the symmetrical phase of Fig. 6, expressed in terms of the full-load current of the machine, plotted against time and extended until the final steady value is almost reached. The equation of this curve is

$$I_t = 4 \cdot 44\epsilon^{-t/0 \cdot 035} + 6 \cdot 07\epsilon^{-t/0 \cdot 6} + 0 \cdot 6 \quad . \quad (7)$$

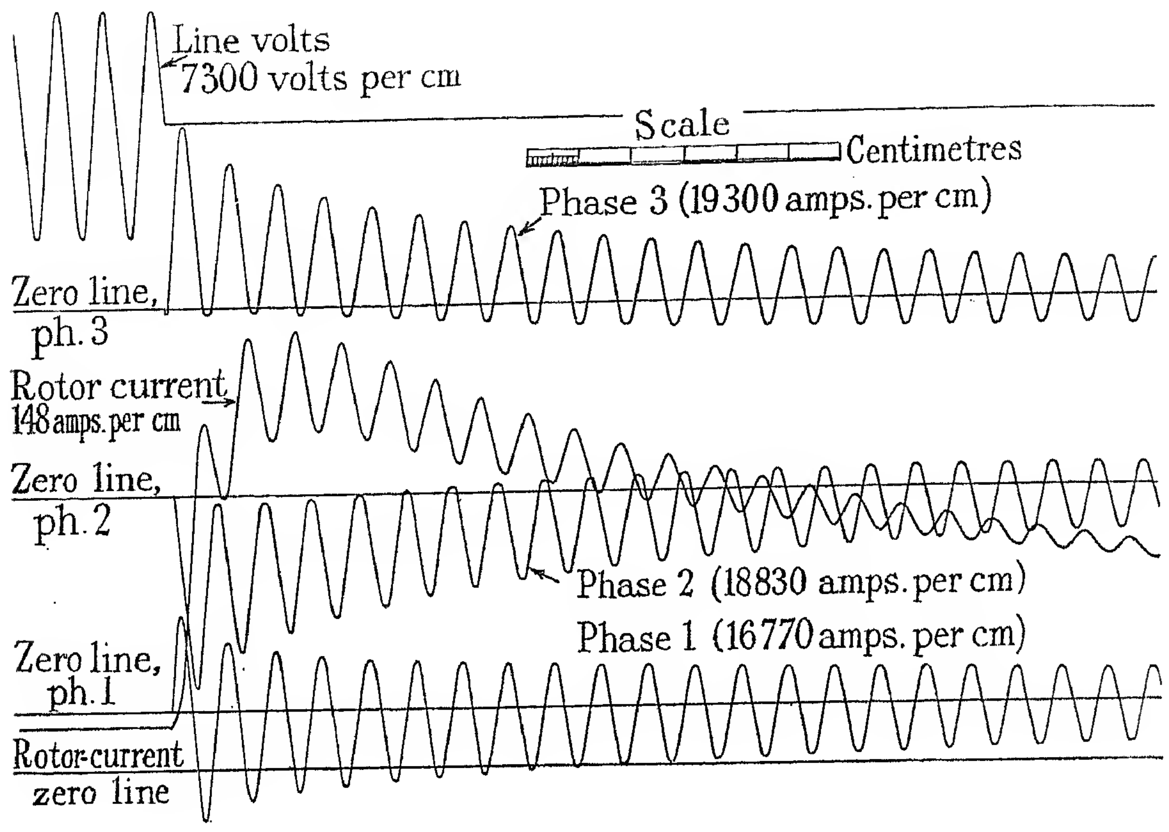

Fig. 6.—Instantaneous 3-phase short-circuit at full voltage, no-load, of 40 000-kVA 10 500-volt 50-cycle 3 000-r.p.m. turbo-alternator.

from which, and the general equation (4), it may be deduced that the values of X_0, X', and X'' are 167 per cent, 15 per cent, and 9 per cent respectively, based on the rated output of the machine. The area under curve (a) has been divided into sections labelled 1, 2, and 3, and the respective intercepts on any vertical line drawn through all three sections give the corresponding values of the first, second, and third terms in equation (7).

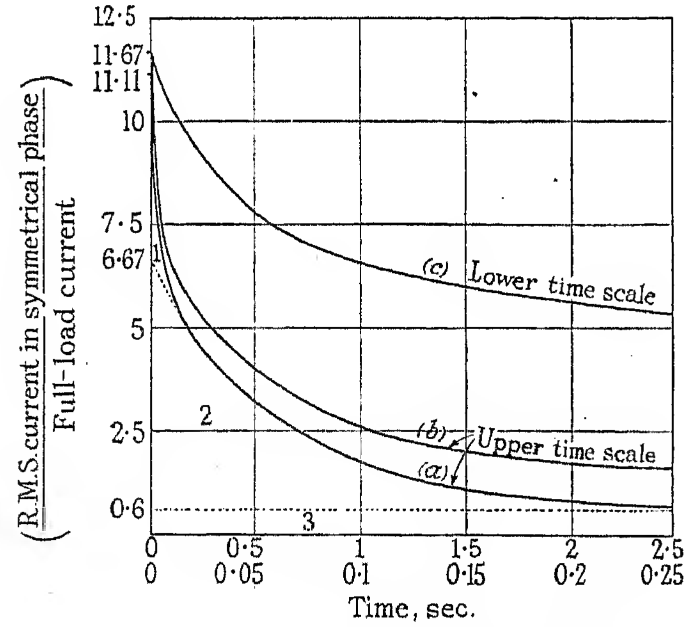

Fig. 7.—Decrement curves of 40 000-kVA turbo-alternator.

Fig. 7, curve (a), refers to an alternator short-circuited at no load, and curve (b) shows the calculated symmetrical r.m.s. current of the same machine short-circuited when carrying rated load at the design power factor (0·825 lagging), assuming rated voltage E_T prior to the fault. For curve (b),

$$I_t = 4\cdot 44\epsilon^{-t/0\cdot 035} + 5\cdot 69\epsilon^{-t/0\cdot 6} + 1\cdot 54 \quad . \quad (8)$$

Curve (c) shows the initial portion of curve (b) to another time scale.

Fig. 8 shows the asymmetrical component of phase 2 (Fig. 6) expressed as a percentage of the initial peak value of the symmetrical current. The equation of the curve in Fig. 8 is

$$I_{tDC} = I_{0DC}\epsilon^{-t/0\cdot 143} \quad . \quad . \quad . \quad . \quad (9)$$

With the exception of the synchronous reactance, the foregoing values of the machine constants are the

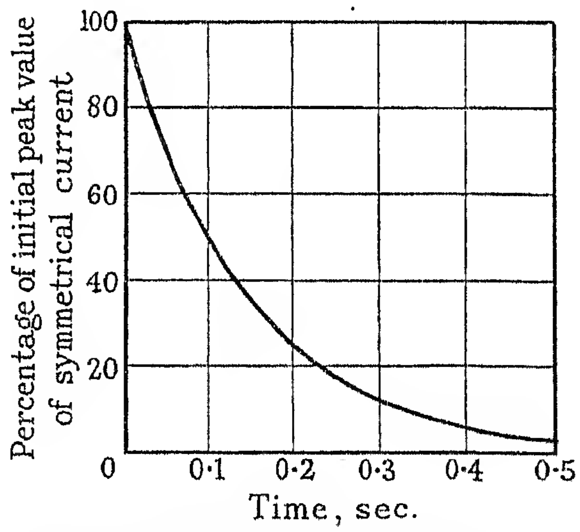

Fig. 8.—Decrement curve for asymmetrical component in phase 2 of short-circuit illustrated in Fig. 6.

saturated values, and are based on the assumption that a sudden short-circuit is applied at the machine terminals. Unfortunately the value of these "constants" is not quite constant for varying degrees of saturation or for faults which include external impedance, though the deviation is such as not to prejudice seriously the estimation of circuit-breaker duty; and hence, for the present

purposes, the relationships given may be used without correction.

(6) FAULTS AT POINTS OF SUPPLY ON INTERCONNECTED SYSTEMS

(a) Some Effects of Interconnection

On an interconnected system, supplied at several points, a fault at one power station is contributed to by remote machines, which, in consequence of the impedance of the intervening interconnectors and transformers, may individually supply little fault current.

In the case where an alternator is short-circuited through an external reactance (X_e), the short-circuit current may be determined as previously described for dead short-circuits if the reactances of the machine are increased by X_e. Thus the sub-transient reactance becomes $(X'' + X_e)$; the transient reactance becomes $(X' + X_e)$; the synchronous reactance becomes $(X_0 + X_e)$; and the transient time-constant T' is increased to

$$\frac{X' + X_e}{X_0 + X_e}T_0$$

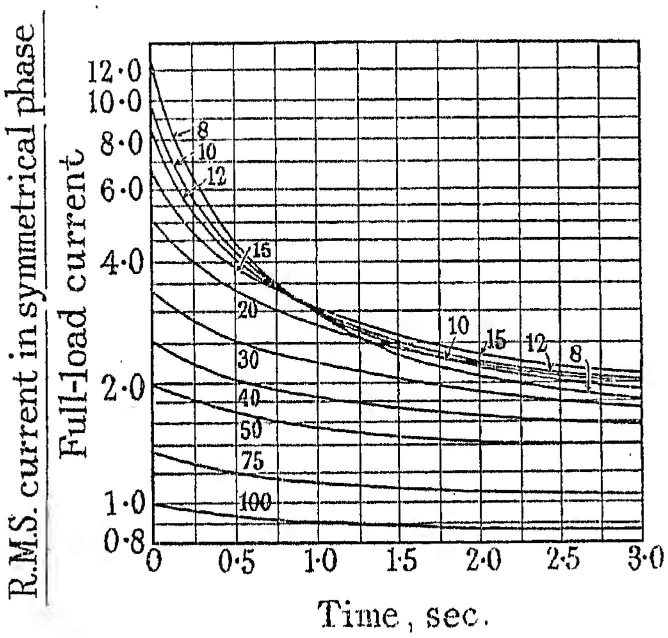

Fig. 9.—Short-circuit decrement curves for turbo-alternators, with and without external reactance. (The number on each curve is the percentage reactance of the fault circuit to which the curve applies.)

The general case where several groups of loaded alternators are supplying fault current through different paths does not admit of such a simple analytical solution. Hahn and Wagner* have investigated this case, and the curves in Fig. 9 are based on their published work. These are the average results from 3-phase 60-cycle alternators at rated-output excitation. The reactances given are the sub-transient reactance of the plant, plus the external reactance, all referred to the total rated output of the alternators. Similarly the expression "full-load current" in Fig. 9 means the aggregate rated r.m.s. current of the machines at 0·8 power factor (lagging). The values given are those of the symmetrical fault current, and should be corrected for asymmetry where necessary. The curves were determined for conditions where the interconnectors were overhead lines, and caution is necessary in applying them to cases where underground cables are used for this purpose. Reactances up to 15 per cent are assumed to be located in the machines, values above this figure being external.

* See Bibliography, (4).

Where the intervening reactance is considerable, the reaction of the relatively small fault current does not materially affect the generated e.m.f. in the remote machines, and, on fault interruption, full circuit voltage is rapidly restored. This restoration is not instantaneous at the circuit-breaker terminals, because, when the fault is interrupted, the generated e.m.f. in the local machines being reduced according to the decrement and the interconnectors being at full voltage at the remote ends, an equalizing current is supplied to the local machines which incrementally accelerates the restoration of full voltage local to the circuit breaker. During the first complete half-cycle after interruption, the recovery voltage assumes a value intermediate between that for isolated working and full circuit voltage. For given conditions this value may be calculated. In general, it may be stated that the actual duty of power-station circuit breakers, in interrupting a circuit carrying a given current, is more severe under interconnected than under isolated working conditions.

(b) Characteristics of Generating Plant

One of the most important considerations emerging from this brief analysis of short-circuit phenomena at power stations is the very high initial value of the fault current. Hitherto many purchasers' specifications for generating plant have only requested the manufacturer to state the inherent steady-state reactance of the alternator winding, in which due allowance is, quite properly, made for the effects of stator and field flux-leakage under steady loading. Under the conditions which immediately follow fault inception, field leakage is negligibly small; and hence the sub-transient reactance, which determines the value of the initial symmetrical fault current, is very nearly equal to the reactance due to stator leakage only. The transient reactance takes account of stator and field leakage at a time when the rotor eddies have subsided, yet the m.m.f. of the field winding is still very high; consequently the field leakage at this stage is appreciably greater than that under steady excitation at rated load. The value of X'' is therefore usually lower, and that of X' usually higher, than the effective steady-state reactance.

Hahn and Wagner have shown that $X'' = 0\cdot77X_p$, where X_p is the steady-state reactance at normal voltage, as determined by the well-known Potier method of analysing voltage regulation. The value of X' in terms of X'' is given by equation (2). These average relationships may be of service in determining the constants of older machines for which full design data may not be readily available; but, wherever possible, design and test values should be obtained.

In the case of new machines, the manufacturer should be requested to determine the values of X_0, X', X'', T', T'', and T'''.

(c) Rating of Switchgear

Another matter which emerges is the manner in which the actual switch work involved in interrupting a fault

varies with the time-interval between fault inception and interruption. In an isolated machine or power station without external impedances, the current and recovery voltage are so reduced at the end of 2 sec. from fault inception that the kVA to be interrupted, measured in terms of these two quantities, rarely exceeds the continuous rating of the plant supplying the fault. This is still true when voltage regulators are employed, provided the exciters are not designed for an exceptionally high "ceiling" voltage.

On interconnected systems, the current and voltage of the local machines are decremented, but, on interruption, the recovery voltage tends to rise rapidly. Where the fault circuit includes external impedance, the decrement in both current and voltage is restricted.

The possibility of thermal injury to insulation, and the instability of synchronous plant on sustained low voltage, preclude the adoption of time-intervals of the order of 2 sec. on all important circuits, and instantaneous protection is recommended wherever possible. With so-called instantaneous protective systems the time-interval between fault inception and interruption averages about 0·2 sec. and, taking half of this value to cover differences in switchgear design and inadvertent operation, it might seem that the 0·1-sec. point on the appropriate decrement curve would give a safe upper-limit value of the current to be interrupted. The main contentions against such a method of assessing circuit-breaker duty are: (i) Some faults grow from minor to major faults during the initial period, and may reach their maximum value at the instant of interruption. (ii) The method demands such a high (Making current/Breaking current) ratio that the making duty often constitutes the limiting feature of the design, and little is gained by specifying the reduced current to be interrupted.

With regard to (i), the nature of the phenomena is such that the maximum value of the short-circuit current is controlled by the ability of the rotor eddies to suppress field leakage, and hence by the rate at which the fault current rises. For a given circuit, faults gradually applied do not reach the maxima attained by faults instantaneously applied.

The author's view is that the 0·1-sec. value on the appropriate decrement curve gives a safe upper limit for the current to be interrupted, provided the decrement is based on the highest pre-fault busbar voltage and rated output excitation on all machines. The switchgear designer should be informed of the corresponding maximum instantaneous peak current.

Since the prevailing tendency is for isolated systems to become interconnected, the latter might well be regarded as the general case. Hence, it would seem that if advantage is to be taken of the easing of switch work due to the decrement when assessing the required rupturing capacity of switchgear at points of supply, it is the reduction in current rather than the more problematical reduction in recovery voltage which should be used. The incompleteness of present knowledge as to the magnitude and quantitative effect of the restriking transient voltage is a further reason against the admissibility of assuming a decremented recovery voltage on interconnected systems.

In all cases the circuit breaker should be capable of being closed and of remaining closed on the maximum instantaneous asymmetrical peak current.

(7) NETWORK FAULTS

Here the impedance of the network between the energy source and the fault restricts the fault current and, hence, the decrement of the alternators. The higher the power factor of the fault circuit, the smaller the reaction per ampere of stator current, and consequently the restricted decrement is most evident where, as in cable networks, the fault-circuit impedance is substantially resistive. Fig. 10, based on Hahn and Wagner's work, shows the decrement in symmetrical current which may be expected on cable networks. The ordinate in Fig. 10 is the percentage to which the initial symmetrical fault current is reduced at the stated time-intervals from

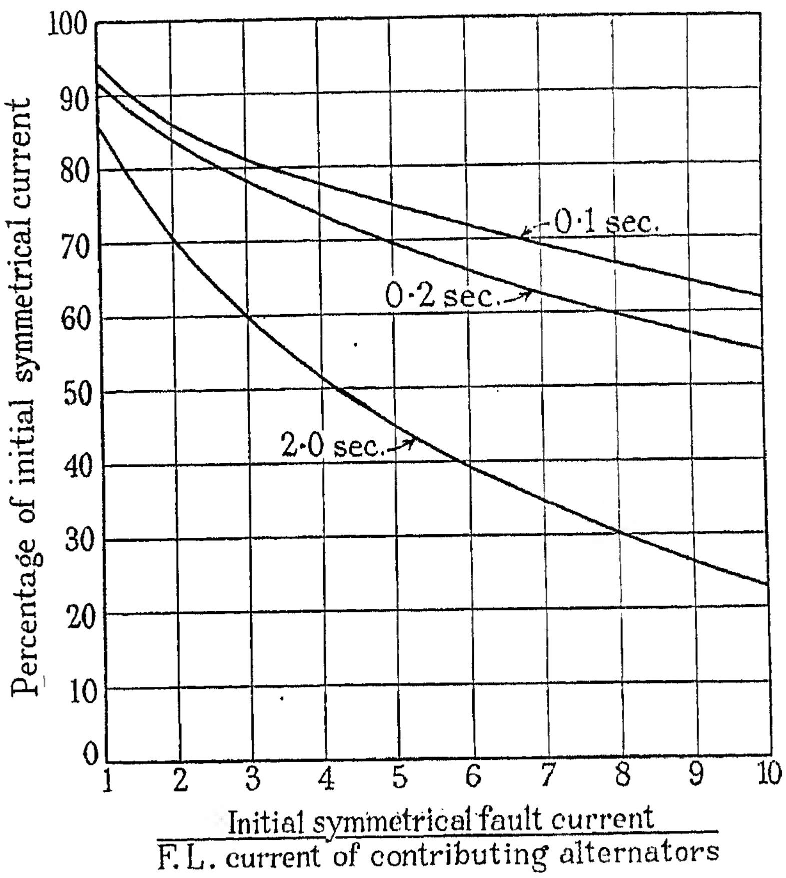

Fig. 10

fault inception, whilst the abscissa is the initial value of the symmetrical fault current expressed in terms of the full-load current of all the alternators contributing to the fault.

The time-constant (T''') and corresponding power factor of a fault circuit are given in Table 1.

At the end of a time-interval, from fault inception, equal to the time-constant of the fault circuit, the d.c. component of the short-circuit current has fallen to 36·8 per cent of its initial value, and at three times this interval the d.c. component has only 5 per cent of its initial value. The power factor of fault circuits on cable networks ranges from 0·1 to 0·5 lagging, and, from Table 1, it is evident that the d.c. component at the time of circuit interruption (0·1 sec.) is negligible over this range of power factor.

The instantaneous symmetrical short-circuit current, contributed by the connected generating plant to any point on the network, may be calculated by summating

vectorially the impedances of alternators, reactors, and network, between the energy-source and the fault, and dividing the resultant impedance into the generated voltage. This value, adjusted in accordance with the 0·1-sec. decrement curve of Fig. 10 for the appropriate conditions, may be taken as the current contributed by the generating plant at the instant of rupture.

In the case of networks supplying synchronous convertors, or large induction motors, the short-circuit current is augmented by the back feed from these machines. A running convertor short-circuited on the a.c. side behaves in a similar way to an alternator and delivers an instantaneous current inversely proportional to its sub-transient reactance. This current is decremented according to the time-constants of the machine. The average sub-transient reactance of motor convertors of normal design has been found, by calculation, to be 25 per cent for machines with completely enclosed stator and rotor slots on the alternating-current end, and 20 per cent for machines with open slots. The percentage reactance of transformers supplying rotary convertors is usually indicated on the rating plate, and a further 5 per cent added to this value has been found to give a close approximation to the reactance of the set. The reactance of induction motors varies somewhat, but, in any given case, may be deduced from the manufacturer's design or test data.

In order to clarify the position it would seem desirable for the purchaser's specification to set out clearly the circuit voltage, the frequency and system of supply, the system earthing arrangements, the normal current of the circuit, the maximum instantaneous asymmetrical peak current, the r.m.s. symmetrical current at the instant of rupture (0·1 sec. from fault inception), the maximum asymmetrical d.c. component (in amperes) which may be present at the instant of rupture, and the average r.m.s. current during 5 seconds following fault inception, assuming complete asymmetry initially.

All these quantities should refer to the ultimate conditions likely to obtain on short-circuit at the point under consideration, with maximum busbar voltage and all generators carrying rated-output excitation.

The manufacturer's test certificates should then show that the design of switchgear offered has been successfully subjected to an agreed number of approved duty-cycle tests, which, separately and collectively, demonstrate the performance of its various components under all fault conditions up to and including those envisaged in the purchaser's specification. These tests should be carried out on a circuit in which the power factor is not greater than 0·1 lagging, the recovery voltage is 100 per cent of the specified circuit voltage, and the natural frequency is at least 25 000 cycles per sec. No condenser or other circuit-modifying device should be connected in parallel with the circuit breaker under test. The duty cycles should include the closing of the circuit breaker against the maximum asymmetrical peak current.

Table 1

Power factor of fault circuit (lagging)	0·05	0·1	0·2	0·3	0·4	0·5
Time-constant of d.c. component (T'''), in sec. ..	0·061	0·03	0·015	0·01	0·007	0·0055

If the short-circuit is applied close to the a.c. terminals, the current decrement of all these machines is such that the 0·1-sec. value will not exceed 60 per cent of the instantaneous current. The d.c. component at 0·1 sec. will not exceed 50 per cent of the instantaneous symmetrical peak current.

The effects of such plant should be taken into account in estimating circuit-breaker duty on networks. In all cases 100 per cent recovery voltage should be assumed.

(8) SWITCHGEAR SPECIFICATION AND TESTS

From the foregoing it will be noted that the task of estimating the circuit-breaker duty at any given point on a network is complex. All that is possible in the present state of the art is to assign specific values to the more important variables which will cover the most severe conditions to which the apparatus will be subjected in service. The only satisfactory manner in which switchgear can be proved to be capable of performing the specified duty is by means of full-scale tests, and it is a matter for gratification that several of the larger British manufacturing groups have now provided equipment for this purpose. The position is not quite so happy with regard to the form and number of tests necessary to prove a circuit breaker, or the calculation of the rating of circuit breakers from the oscillographic test records. In this connection, it is perhaps a little unfortunate that such ratings have in the past been expressed in kVA without supplementary details concerning a number of vital circuit constants and test details.

(9) LIMITATION OF FAULT CURRENT

Owing to the growth and interconnection of systems, the possible fault current at points of supply has increased to such magnitude that the cost of switchgear adequate to deal with it constitutes a disproportionate share of the distribution charges. This applies particularly to 6·6-kV and 11-kV systems where, in many cases, it is imperative that measures should be taken to limit the current.

On new layouts this may be effectively accomplished by adopting a higher operating voltage, and there is much to commend such a procedure, but, in existing power stations, it may not be practicable technically or economically to carry out such a change. Nevertheless, in these stations a good deal may often be effected by the introduction of suitable current-limiting devices; in preserving the utility of existing switchgear, minimizing the cost of new switchgear, and providing a higher overall factor of safety in the reliability of supply.

Four arrangements of reactors are shown in Fig. 11, of which those in (*a*), (*b*), and (*c*) reduce the short-circuit current at the busbars, whilst (*d*) relieves the network only. In Fig. 11(*a*) a reactor is shown in series with each alternator. By suitable choice of reactors the instantaneous short-circuit current of each machine may be limited to any desired amount without imposing any restrictions on the manner in which the busbars may be

coupled either at the station or via the network. The main disadvantage of this method is that there is a continuous energy-loss in the reactors, and a higher e.m.f. must be developed in the machines, on all lagging power-factor loads, to compensate for the in-phase reactor "drop," thus introducing further energy loss in the exciter, rotor winding, and stator iron of the alternators.

The layout shown in Fig. 11(*b*) presupposes that there are two sets of busbars, and that the plant may be connected to either at will. With a reactor connected as shown, there is the electrical equivalent of two interconnected power stations, and the well-known limitations on further interconnection through the network are at once imposed. In practice, such further interconnection is usually avoided and the local system is operated as two independent units. In normal working, the energy-transfer through the reactor may be controlled by judicious grouping of the plant and feeders, and the sets of busbars may be maintained at equal voltages by controlling the reactive current passing through the reactor. Thus by the introduction of one reactor, of suitable ohmic value and current rating, the instantaneous short-circuit current at either set of busbars may be materially reduced, without entailing any increase in the generated e.m.f. or excessive reactor losses, though at the sacrifice of some network flexibility. Should the reactor be controlled by means of an automatic circuit breaker fitted with time-lag overload protection, the two halves of the system may be automatically separated in the event of a sustained fault on either; a feature which tends to ensure continuity of supply to the healthy half.

Fig. 11(*c*) shows an elaboration of the method already described in connection with Fig. 11(*b*). Here two lines of busbars are indicated—one sectionalized by automatic circuit breakers, and the other by non-automatic switches. Normally, the alternators and feeders are connected to their respective sections, and further interconnection between sections, via the network, is avoided. In the event of failure of any section of busbar it could be automatically isolated by suitable protective arrangements, and, if each alternator and feeder is capable of being switched on to the solid or hospital set of busbars, the supply to the feeders of the faulty section may be restored and maintained until such time as the fault has been rectified. Inter-section circuit breakers are shown, and it may be desirable to close one or more of these, at times of light load, when a reduced number of alternators are in service.

Fig. 11(*d*) shows individual reactors on outgoing group feeders, which improve the system stability and reduce the current on network faults at the expense of relatively poor voltage regulation under normal working. On large systems where the voltage is automatically controlled at points on the network side of these reactors, the above-mentioned limitation should not prove serious, but, on smaller systems, other methods, discussed in detail in a later section, have been found more expedient in reducing the network fault current.

It is difficult to generalize on the net saving which may be effected by the use of reactors. Each case forms an individual problem wherein the reduction in capital costs is partially offset by the capitalized value of reactor losses, and, in a less tangible way, by the negative value of poorer regulation and decreased network flexibility. Table 2 shows the relative costs, per 3-phase panel, of certain sizes of single-busbar 11-kV metalclad electrically-operated switchgear, erected on site but not cabled up. The technical particulars, and relative costs per 3-phase bank, of some equivalent-duty reactors are given in Table 3. These costs also include erection on site but exclude cabling. The percentage costs in Tables 2 and 3 are on a common basis. From the information given, with a knowledge of the cost of a particular size of 11-kV switchgear and of the prevailing supply tariff, it should be possible to compute, to a first approximation, the relative costs of some alternative arrangements.

It requires to be emphasized that, for all applications, reactors should be at least as reliable under short-circuit as the switchgear they protect, and only those designs which have withstood short-circuits, at full voltage under

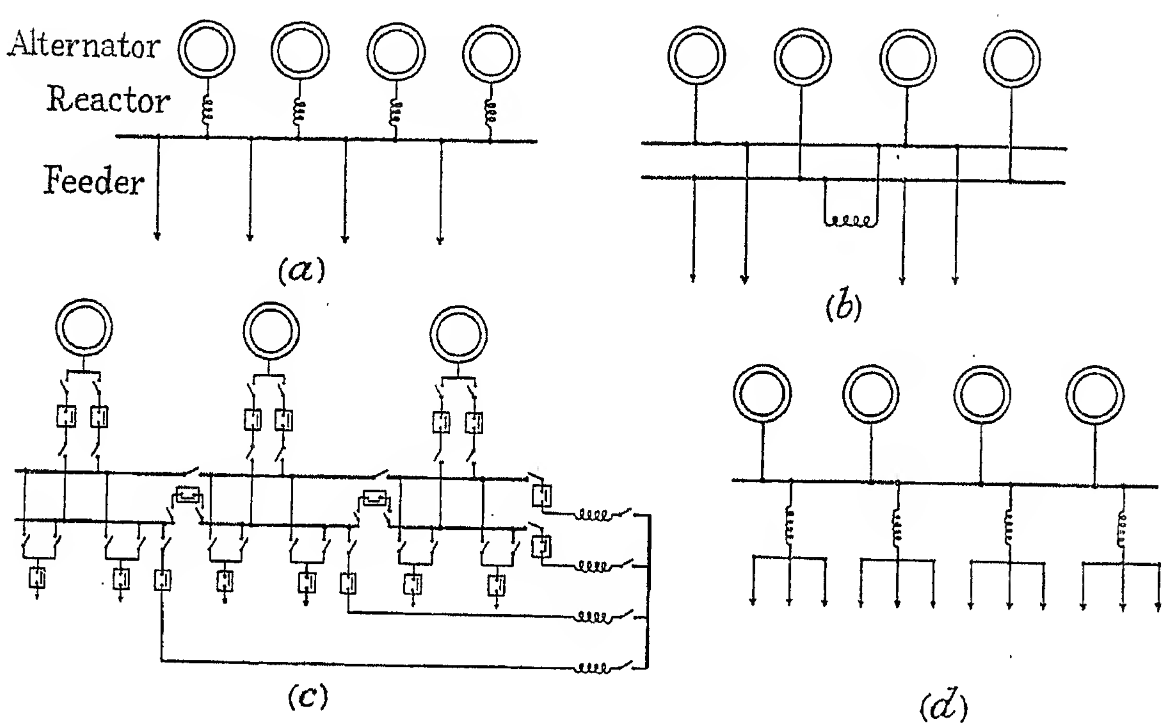

Fig. 11

rigidly specified conditions, should be installed. The ohmic value of the reactance should be independent of the current passing through the reactor.

(10) SWITCHGEAR AT POINTS OF SUPPLY

(a) Physical Layout

The practicable or economic limit to the reduction in short-circuit current having been reached, consideration may be directed towards a switchgear layout which will safely control the supply without unduly loading the capital account of the undertaking. In the matter of safe control it is being increasingly demonstrated, under the present tendency to provide relatively few sources, each of high-energy content, and to supply large networks from a single point, that the physical layout of switchgear at such points ranks equally with its technical design.

Such switchgear should be sectionalized, both physically and electrically; the former, by providing a separate room or even a separate building for each section; the latter, by means of circuit-breaker-controlled current-limiting devices between sections. Each such room should be so constructed that the consequences of an explosion or oil fire within it shall not prejudice the performance of the equipment in any other room. Direct interconnectors between sections should be metalclad throughout, and be capable of interruption by remote-controlled circuit breakers, or switches, located in chambers completely isolated from the adjacent switch-rooms. Fig. 12 shows a plan view of a suggested switch-room layout suitable for the sectionalizing scheme shown in Fig. 11(*c*). The reactors would be located in separate chambers outside the main switch-rooms.

The switch panels in each section should be segregated in a manner best calculated to localize the scattering of liquid in the event of a tank failure, and a high-capacity drainage-pipe connection should be suitably arranged in the floor under each circuit breaker for the rapid removal of such liquid outside the building. An efficient fire-fighting appliance should be provided, capable of selective automatic operation, and of alternative hand operation from the outside of each switch-room. It should be

Table 2

RELATIVE COSTS PER PANEL OF 3-PHASE SINGLE-BUSBAR 11-KV METALCLAD COMPOUND-FILLED SWITCHGEAR

Size	Rupturing capacity	Relative cost	Size	Rupturing capacity	Relative cost	Size	Rupturing capacity	Relative cost
amps.	MVA	per cent	amps.	MVA	per cent	amps.	MVA	per cent
400	150	100	1 000	500	340	2 000	500	400
400	250	133	1 000	750	625	2 000	750	710
400	350	180	1 000	1 000	1 190	2 000	1 000	1 270
400	500	280	1 000	1 500	1 470	2 000	1 500	1 530

Table 3

TECHNICAL PARTICULARS AND RELATIVE COSTS OF 11-KV 3-PHASE REACTORS*

Continuous rating	MVA reduced from/to	Full-load loss	Percentage regulation		Impedance	Relative cost
			Unity p.f.	0·8 p.f.		
amps.		kW			ohms per phase	per cent
2 000	1 500/750	36	0·1572	2·225	0·1125	480
2 000	1 500/1 000	19	0·058	0·807	0·0405	405
1 000	1 500/750	9	0·0555	0·805	0·081	390
1 000	1 500/1 000	5	0·0265	0·402	0·0405	370
400	500/250	3·5	0·046	0·952	0·242	123
400	500/350	2·5	0·033	0·422	0·104	123
400	350/150	10·25	0·135	1·86	0·462	115
400	350/250	3·3	0·0435	0·569	0·139	117
400	250/150	8·25	0·1085	1·311	0·323	103

* Percentage costs are on same basis as switchgear costs given in Table 2.

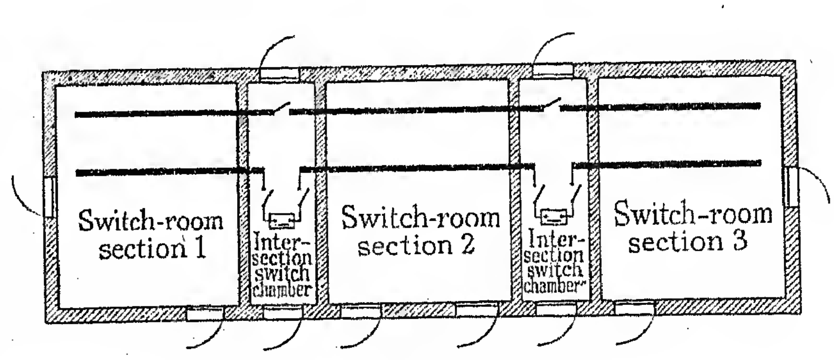

Fig. 12.—Plan of switch-room.

impossible for liquid to pass from the switch-room to the cable basement. All inflammable serving should be removed from cables up to the point of their emergence from the building. Inside the building each cable circuit should follow a separate route, and where this route is via a cable trench the latter should be filled with sand or pebbles.

Control cables should be armoured, and be located as far as possible from the actual circuit breakers, and carried outside the switch-room in fireproof enclosures by the shortest possible route. In no case should communication circuits pass through the switch-room.

To those who may be labouring under the practical limitations of existing layouts, these recommendations may represent an impossible ideal, yet even here some improvement may often be effected by carrying out the simpler and less expensive suggestions. In new layouts the foregoing recommendations represent, in the author's view, the minimum requirement for reasonable safety.

The accumulating experience in this and other countries seems to show that, where such sectionalizing cannot be carried out, all large urban networks should be provided with not less than two points of supply. Such points may normally be interconnected through an e.h.t. system but each must be capable of providing at least a partial supply to the whole network when the other, with its associated energy source, is out of action. The discovery of a satisfactory insulating fluid of a non-combustible nature for use in circuit-breaker enclosures would also be a contribution to continuity of supply.

(b) Economic Considerations

The most economical switchgear arrangement for controlling a network depends on the maximum available short-circuit current at the point of supply. The simplest layout is one in which each feeder is controlled by means of a proved circuit breaker of adequate making and breaking capacity. This may also be the most economical layout at points of supply where the r.m.s. short-circuit current at rupture is less than 30 000 amperes, but for higher current values a more detailed analysis of the problem will usually be repaid.

Already in Fig. 11(*d*) a group-controlled feeder scheme, employing current-limiting reactors, has been indicated, and a further method of feeder control will now be described. This consists in providing a circuit breaker (F.C.B.) of relatively low rupturing capacity for each feeder, and so arranging the layout that groups of three of these units are supplied from the main busbars through a master circuit-breaker (M.C.B.) capable of making and breaking the short-circuit current at the point of supply.

The control gear for such an equipment might be so arranged that, on the occurrence of a fault on any feeder of a group, the M.C.B. opens first, followed immediately by the opening of the F.C.B. on the faulty feeder; thereafter the M.C.B. automatically recloses. It should be stated at once that the F.C.B.'s are not ordinary low-rupturing-capacity units, but must have conductors proportioned and braced to carry the maximum possible asymmetrical peak current at the point of supply. The required rupturing capacity is determined by the possible current due to the back feed from the remaining healthy feeders of a group after the M.C.B. has opened, but the severe current-carrying condition may be the limiting feature of the design, and to meet this requirement it is sometimes necessary to provide a higher-rupturing-capacity unit than that determined by the back feed to be interrupted. Notwithstanding this limitation, it will usually be found that the switchgear cost for such a group control scheme is substantially less than that of providing a separate high-rupturing-capacity circuit-breaker for each feeder. In a particular case where five M.C.B.'s of 1 500 MVA rupturing capacity and fifteen F.C.B.'s of 350 MVA nominal rupturing capacity were installed, the cost was 55 per cent of that of an alternative installation, employing fifteen 1 500-MVA breakers. In lieu of this financial concession there is a sacrifice of some of the flexibility of unit control, and the network must be designed to withstand the momentary loss of two healthy feeders.

Fig. 13 shows a simplified line diagram of a possible control circuit for such a scheme, the sequence of operation of which is as follows: The protective relay 5 closes the two contacts 5_1 and 5_2; the first of these trips the M.C.B., and the second trips relay 6. The M.C.B. opens its own coil circuit and energizes the trip coil of the F.C.B. through the auxiliary contact of the latter and the contact of relay 6. It also energizes the time-delay relay 7. Relay 6 opens its own coil circuit and closes two contacts. The F.C.B. trips, opens its own coil circuit, opens one auxiliary switch, and closes one auxiliary switch. Relay 7 recloses the M.C.B. through an auxiliary contact on the faulty feeder F.C.B., a contact of relay 6, and two contacts in parallel—one on each healthy F.C.B. Relay 6 is reset by hand.

The scheme shown employs a minimum of apparatus for solenoid-operated switchgear, though for certain motor-operated M.C.B.'s the reclosing relay 7 could perhaps be omitted. It is a moot point whether or not the reclosing relay should be endowed with a time-delay feature. Since the fault is completely isolated at the point of supply as soon as the F.C.B. opens, the M.C.B. could be safely closed immediately thereafter, thus minimizing the time of loss of supply through healthy feeders. Against this, there is the view that a small but definite time-delay in the restoration of healthy feeders is of little disadvantage to a stable network, and is of value in that the transient state inseparable from a major fault is allowed to subside before the M.C.B. is reclosed. A time-delay of 1 sec. is suggested for this service.

It cannot be too strongly stressed that in such a scheme a minimum of apparatus which will perform the prescribed duty should be employed. Although modern relays of reputable make are reliable they are of necessity comparatively delicate instruments, and to multiply their number on unessential services introduces an unwarranted risk of failure.

The following are some of the points which experience has shown to be worthy of note in connection with such a scheme.

Conductors.—Electromagnetic forces must be withstood, and the thermal-storage capacity must be such that there is no tendency for contacts to weld under through fault. Bar-type current-transformer primaries should be employed, and, in the case of metalclad filled switchgear, the author recommends the use of solid

compound for busbar and current-transformer chambers because of the enhanced mechanical rigidity thereby obtained.

Operating mechanism.—All circuit breakers should be remotely operated, and, if it is impracticable to design an F.C.B. mechanism to close against the full fault current, the operating instructions should ensure that where there is the least doubt whether the dead feeder is healthy it should be switched in by the M.C.B., or, when this is inconvenient, be made alive at the remote end.

Control gear.—All auxiliary contacts on the switchgear should be of very robust construction. Contacts which are normally open, should be connected in the control circuit on the positive side of the coil which they control, to minimize the tendency towards anodic corrosion of these coils. This latter is a phenomenon more prevalent in damp atmospheres whereby microscopic leakage current from a positively charged winding ultimately corrodes the fine wire sufficiently to open-circuit the coil. If the coil is at zero or negative potential to earth the effect does not appear, presumably, in the latter case, because the coil forms the cathode in any electrolytic couple to earthed metal. As a further precaution, control rooms should be kept at a moderate even temperature, preferably under thermostatic control.

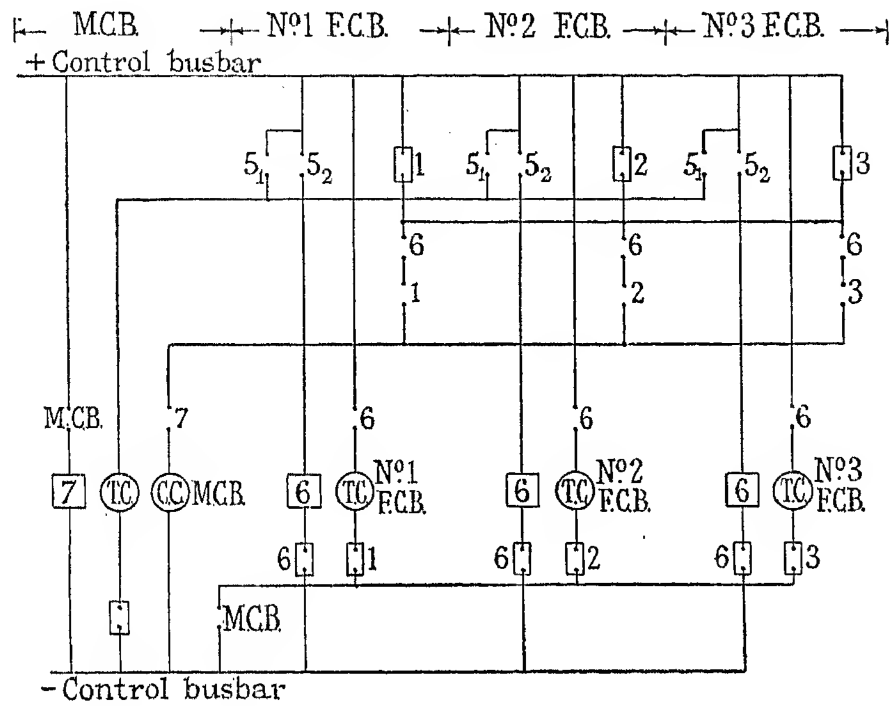

Fig. 13.—Schematic diagram of control circuits for group control sequence tripping and automatic reclosing.

M.C.B. = Master circuit-breaker.
F.C.B. = Feeder circuit-breaker.
C.C. = Closing coil.
T.C. = Trip coil.

= Solenoid. = Relay. = Relay contact normally open, auxiliary contact closed when circuit-breaker open.

= Relay contact normally closed, auxiliary contact closed when circuit breaker closed.

(11) HIGH-VOLTAGE CABLE NETWORKS

An efficient high-voltage cable network should admit of loading all active copper to its thermal limit, normal division into radial sections to restrict power concentration and limit the zone in case of failure, and adequate mutual standby supply between sections to provide for any reasonable eventuality.

The safe loading of a cable is determined by the type of cable; the method of laying, e.g. direct or in ducts; the position, loading, and arrangement of adjacent cables; the class and moisture content of the soil; and the loading cycle. The last authoritative general statement on the safe loading of buried cables was contained in a report issued by the Electrical Research Association in 1923.* Since that date, a further British Standard Specification for High-voltage Cables has been issued,† and it is understood that an extensive research on cable heating has been in progress for some time past, on which another E.R.A. report will shortly be made.

Perhaps the most difficult problem is to equate conductor-temperature to cable-life and thereby determine the most economical temperature-rise. In this country the safe temperature-rise in buried cables has hitherto been taken as 50 deg. C., though in American practice a considerably higher value is used. The measurement of conductor temperature under changing load and variable thermal resistivity of the soil (g) is a matter of some practical difficulty. The average temperature, determined from conductor resistance, gives little indication of hot-spot temperatures, which are the vital quantities. These latter may be determined to a close approximation by an exhaustive set of readings taken on the cable armouring at frequent intervals along the route. Assuming the thermal resistivity of the soil is known, the conductor temperature may readily be deduced from such readings. A low estimate of g gives a calculated conductor temperature higher than the actual, and vice versa.

In view of the financial importance of being able to obtain the maximum output from high-voltage cables, at

* See Bibliography, (8).

† B.S.S. No. 480—1933.

the prevailing load cycle, without exceeding a temperature-rise of 50 deg. C., the author has taken, by means of thermocouples, a series of readings of armouring temperatures over a portion of the route where, owing to the nature of the soil and the cable grouping, the cooling conditions were known to be most unfavourable. The current in excess of the value for continuous loading which may safely be carried by any given cable depends on the section of conductor, the design of cable, the value of g, and the daily load cycles. Such overload values cannot, therefore, readily be given in a form suitable for general use.

The grouping of cables in a common trench reduces the excavation cost per cable but permanently reduces their carrying capacity, and it is a problem in economics to determine the cheapest arrangement per ampere transmitted. In congested city streets there is often no alternative to grouping. When a number of main feeders are being laid simultaneously, it is sometimes economical to excavate a common trench to a point where the cables naturally diverge to their respective terminations. In such cases, the cost per ampere of safe loading has been reduced by increasing the section of conductor in the grouped cables over that of the cables in single tracks. Thus 0·4-sq. in. grouped feeders might become 0·3-sq. in. or even 0·25-sq. in. beyond the point of divergence. Where possible, grouped cables should not be spaced less than 8 in. apart. In no case should a feeder of uniform section be laid partly in the ground and partly in ducts, as this practice limits the capacity of the whole feeder to the safe loading in ducts. The author holds the view that, wherever possible, high-voltage cables should be laid directly in the ground. It is realized, however, that where ducts exist throughout the whole route, it may sometimes be cheaper per ampere of safe loading to pull in a larger cable than to open up the ground and lay a smaller cable; and where this is so, technique should be subservient to economics.

The division of high-voltage networks into radial sections, normally completely separated except at the point of supply, would seem to be the safest and most practicable manner of reducing the short-circuit current at substations, and hence of controlling the cost of substation switchgear. Short tie lines, normally open at one end, should be provided between sections to render mutual assistance under emergency conditions such as the loss of a main feeder in either section.

Two main considerations should be kept in mind: (*a*) The sectionalizing should not materially reduce the factor of safety in continuity of supply. (*b*) The network should be so planned that, as additional feeders become necessary, the sections may be subdivided to preserve the short-circuit current within the predetermined limit. The rapid development of electricity supply renders it imperative to adhere strictly to the implications of consideration (*b*) if the operating safety of existing switchgear is to be maintained and the cost of new switchgear kept within reasonable bounds.

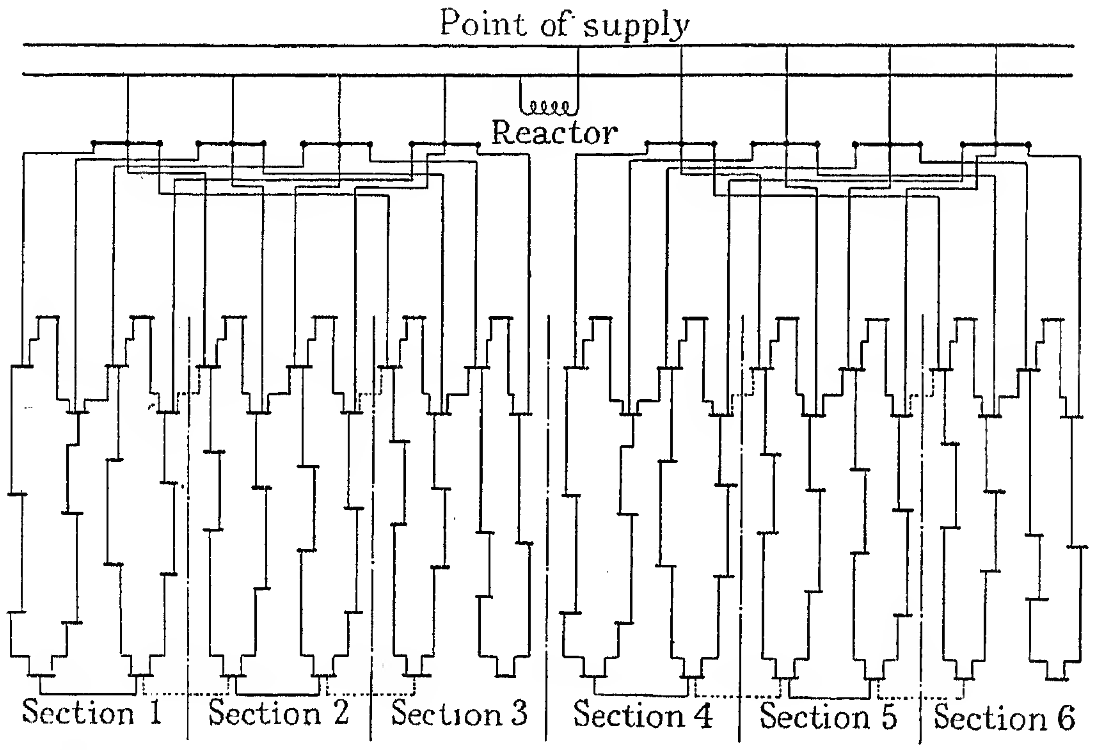

Fig. 14.—Network in six radial sections with group-controlled main switchgear.
Interconnectors shown by dotted lines are normally open at one end.

Fig. 14 shows diagrammatically a typical network divided into six sections, with group-controlled switchgear and a current-limiting reactor at the point of supply. The layout is such that further subdivision is possible, and attention is directed to the fact that only one feeder from each group of switchgear supplies any one section. With a network designed on these principles, it should be possible to limit the short-circuit current at all substations to a definite maximum value. For large 6·6-kV systems, 13 000 amperes at the instant of rupture might form this upper limit, and no difficulty should be experienced in keeping below this figure where the existing network has been moderately well designed. On older networks it may be difficult to work to this value, but if the principle is appreciated and adopted for future extensions a safer and more economical network should evolve.

To obtain the maximum utility from feeder copper,

all main feeders should be of approximately equal length, and each should terminate in a substation where the local load is considerable. A geographical survey of the system loading will determine the optimum terminating zone for main feeders, and the distributive network will radiate from this zone. Substations near to the point of supply may conveniently form a separate section (not shown in Fig. 14) supplied through current-limiting devices of sufficient impedance to reduce the maximum short-circuit current to a predetermined value. Where-ever possible, ring feeds should be provided.

(12) PROTECTIVE GEAR

The most desirable characteristics of protective devices are infallibility of operation, highest possible speed of operation, and highest degree of discrimination.

High-speed operation is essential in the prevention of system instability in all its forms, of synchronous plant from being thrown out of step, and of consumers' motors from tripping on low voltage. It is also of value in preventing or minimizing damage to cables through overheating by fault current. This latter is an effect which may have no apparent immediate consequence, though, if repeated, may reduce the cable life. The curves in Fig. 15 show the temperatures attained by insulated copper conductors plotted against time for different current densities. The calculation is based on the assumption that the whole of the heat generated is stored in the conductor. Thus a 0·1-sq. in. conductor, carrying 10 000 amperes for 2 sec., will experience a temperature-rise of 360 deg. C., which would damage paper insulation adjacent to the conductor. Fig. 16 shows the maximum current which may be transmitted through a 0·1-sq. in. insulated copper conductor, for the given time-intervals, to limit the temperature-rise to the stated values. For conductors of cross-sectional area other than 0·1 sq. in., the maximum current which may be transmitted is determined by adjusting the Fig. 16 values in direct proportion to the cross-section.

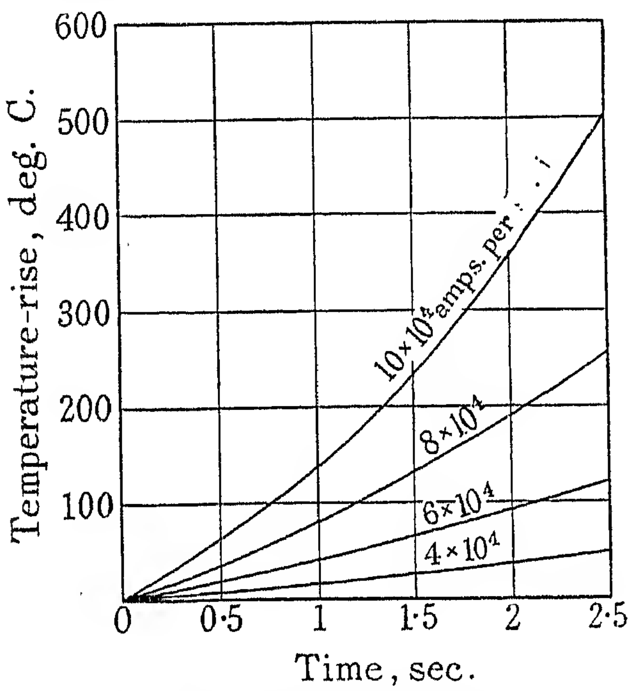

Fig. 15.—Temperature-rise of insulated copper conductors for various current densities.

Highly discriminative protective gear is desirable to ensure that nothing but the faulty feeder or apparatus is isolated. Sectionalized networks have fewer parallel paths than their older prototypes, and, consequently, in the maintenance of supply to the remainder of the section it is of increasing moment that the faulty member alone should be disconnected.

The type of protection which most completely meets these requirements is the balanced system—either with pilot wires, as in many well-known forms, or without pilot wires as in split-conductor or parallel-feeder protection. The author has no doubt whatever that for main feeders and important interconnectors in urban networks this is the only completely satisfactory form of protection. Objection is sometimes raised to systems involving pilot wires on the score of cost. On a recent extension, including six main feeders, each about 7 000 yards long with switchgear at either end, the cost of the balanced-current protective equipment, including relays, current transformers, and pilots, was 4·75 per cent of the cost of the complete electrical equipment comprising switchgear and laid and jointed cables.

Back-up overload protection is desirable on all feeders at the point of supply, and at strategic points on the

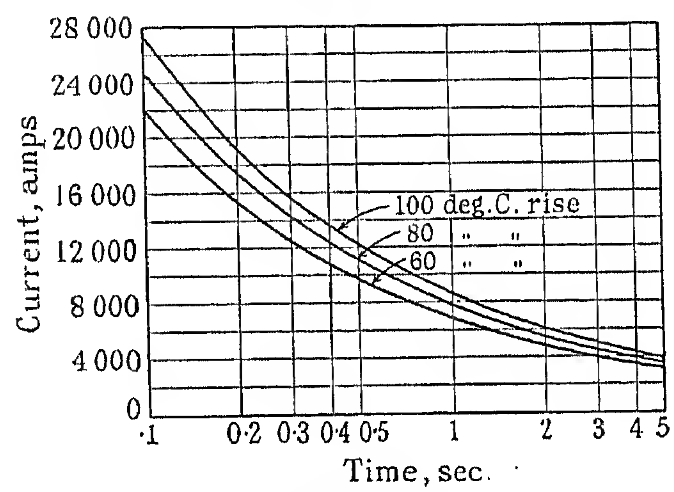

Fig. 16.—Current/time curves for 0·1-sq. in. insulated copper conductor.

network; whilst for certain distributive cables tapped at many points, overload protection may be the only feasible type. On earthed networks, overload and instantaneous earth-leakage protection should be used on all transforming and converting plant, and on dead-ended feeder circuits.

It is recognized that balanced protection is only operative within the "protected zone," which does not usually embrace the switchgear at either end of the feeders. To bridge this gap, a simple form of earth-leakage protection has been used for switchboards on earthed systems. When erected on granolithic floors embodying a bitumastic damp-proof course, the switchboard framework is reasonably insulated from earth and, if insulated glands are fitted to all cables, the only low-impedance path from the switchboard to earth is via the main connection to the substation earth-plate. A bar-type current transformer on this connection will be responsive to earth-fault current from the switchgear, and may be connected on the secondary side to energize an instantaneous relay which operates to trip out all

feeders and thus isolate the substation. This equipment is cheap and selective, and, as most switchgear faults commence as, or rapidly develop into, faults to earth, its utility is considerable.

Where switchgear at the point of supply is sectionalized according to the principles previously discussed, with automatic circuit breakers between sections, this simple form of earth-leakage protection can readily be applied to isolate each section instantaneously on the occurrence of an earth fault on any part of the switchgear comprising that section.

(13) SUBSTATION SWITCHGEAR

The layout of substation switchgear depends on the importance of the substation, and the amount of plant to be controlled. The required making and breaking capacity of circuit breakers is determined, as previously indicated, having regard to future developments. It should, however, be pointed out that the actual values of the duty of all circuit breakers at a given point are not equal. Those controlling plant or spur feeders may be called upon to interrupt the full calculated current; but those controlling incoming feeders will, at most, have to deal with the fault current supplied through the remaining $(n - 1)$ incoming paths. Where rotary plant exists, the back feed on short-circuit must be allowed for in interpreting this statement, though, in general, it is true to say that the duty of circuit breakers controlling incoming feeders is less onerous than that of those controlling plant or spur lines.

Fig. 17 shows a group of typical switchgear layouts, which are self-explanatory; and some of the advantages

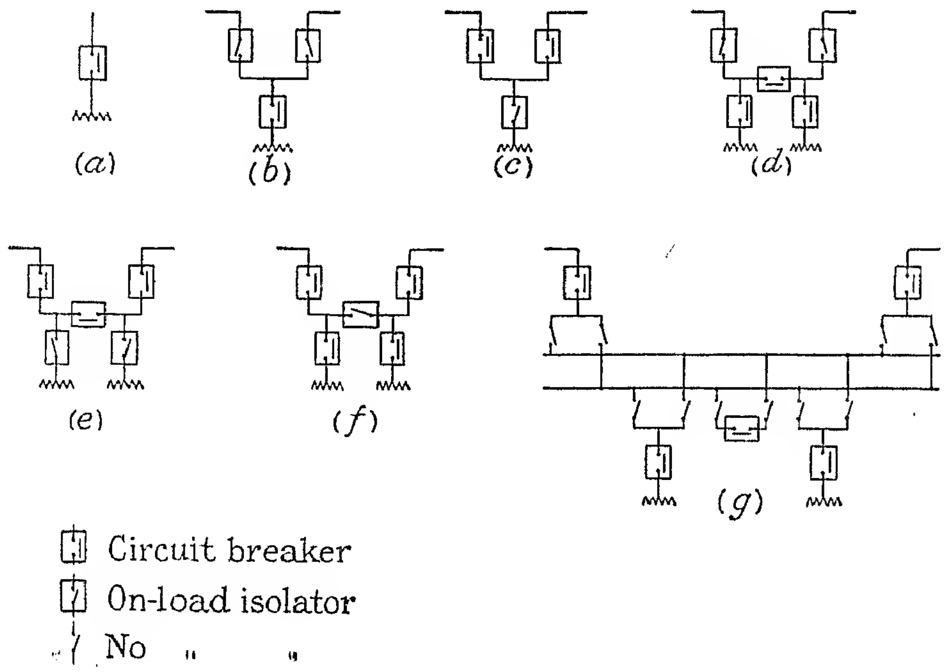

Fig. 17.—Substation switchgear.

Table 4

OBSERVATIONS ON LAYOUTS SHOWN IN FIG. 17

Layout	Suitable for	Each C.B. interrupts: (i) Full short-circuit, *or* (ii) Partial short-circuit	Is balanced feeder protection possible?	Does transformer fault break ring?	Switchgear maintenance facilities	Does single feeder-fault shut down substation?	Relative cost on comparable basis
							per cent
(*a*)	Dead-end feeder	Full	—	—	Poor	Yes	33
(*b*)	Ring main	Full	No	No	Poor	Yes, temporarily	44
(*c*)	Ring main	Partial	Yes	Yes	Poor	No	72
(*d*)	Ring main	Partial on feeder fault, full on transformer fault	Yes	No	Good	No, but shuts down one transformer temporarily	100
(*e*)	Ring main	Partial	Yes	Yes	Good	No	100
(*f*)	Ring main	Partial on feeder fault, full on transformer fault	Yes	No	Good	No	137
(*g*)	Dead end *or* ring main	Dead end—full: Ring main—partial on feeder fault, full on transformer fault	Yes	No	Good	No	191

and limitations, together with the relative costs of the respective layouts are indicated in Table 4. In all cases the guiding considerations should be: (*a*) Adequate making and breaking capacity, proved by full-scale tests. (*b*) Safety for operators. (*c*) Facilities for speedy restoration of partial or total supply. (*d*) Reasonable first cost. (*e*) Good maintenance facilities. (*f*) Suitability for future extension.

True economy will usually be effected in minimizing the quantity, rather than in reducing the quality, of substation switchgear; and, consistent with the desiderata just mentioned, efforts may well be directed toward this end.

(14) TRANSFORMERS

Very few medium-voltage networks are as yet so compact as to admit of the complete loading of one substation being taken over in emergency by adjacent substations. Until this can be done there seems to be considerable merit in placing at least two transformers in each substation providing general supplies. Thus, if one transformer should fail, the remaining unit(s) could carry the load until the inadmissible overload was switched on to adjacent substations. The safe loading of a 2-transformer substation is suggested as 150 per cent of the output of each transformer, and that of a substation having three or more transformers might be taken as the sum of the rated outputs of the transformers. A further advantage of multi-transformer substations is that one or more units may be switched out at seasons of light load and the conversion losses thereby reduced. Transformer sizes could well be standardized, and, for 3-phase 400/230-volt distribution, it is felt that 1 000 kVA is the largest practicable size—the limiting feature being the medium-voltage connections. A range of 1 000-, 500-, 250-, and 100-kVA sizes should meet all requirements.

The operating feature of transformers which calls for most attention is the emission of noise. Much is being done in an experimental way by designers to reduce noise, but the fundamental problem still exists, and, as such, is being attacked by the Electrical Research Association. For some years past the author has specified a maximum flux density in the iron circuit of 11 000 lines per cm^2 as a means of reducing noise. Not only are these low-density designs demonstrably less noisy, but their magnetizing current and iron loss are both sensibly reduced, with corresponding improvement in network voltage regulation and reduction in system maximum demand. The annual saving, due to reduced iron loss, is more than sufficient to defray interest and depreciation charges on the increased cost of the transformer.

The reactance of distribution transformers forms the main current-limiting factor in short-circuits on medium-voltage networks at or near to substations. It is also a factor of considerable importance in determining the voltage variation with load on lagging-power-factor circuits. Current limitation favours a high value of transformer reactance, whilst close voltage regulation demands a low value.

These conflicting requirements may be met by providing low-reactance transformers of moderate kVA rating, and operating a limited group of transformers on each isolated medium-voltage network. Taking 40 000 amperes as an arbitrary upper limit of short-circuit current on a standard 400-volt 3-phase circuit, the required transformer reactance would be 3·33 per cent on 1 000 kVA, 5 per cent on 1 500 kVA, or 6·67 per cent on 2 000 kVA. If, in addition, the normal current in any medium-voltage circuit is limited to 2 000 amperes, this fixes 1 500 kVA as the maximum permissible rating of a paralleled group. On these assumptions, 1 500 kVA of transforming plant having 5 per cent reactance is the maximum rating which should be operated in parallel on the medium-voltage side.

The design of heavy-duty high-rupturing-capacity medium-voltage switchgear is a matter of considerable practical difficulty, and, although the limiting currents referred to above have been chosen arbitrarily, it may well be that, in the present state of knowledge, values of this order form an upper safe limit for economic design of such switchgear.

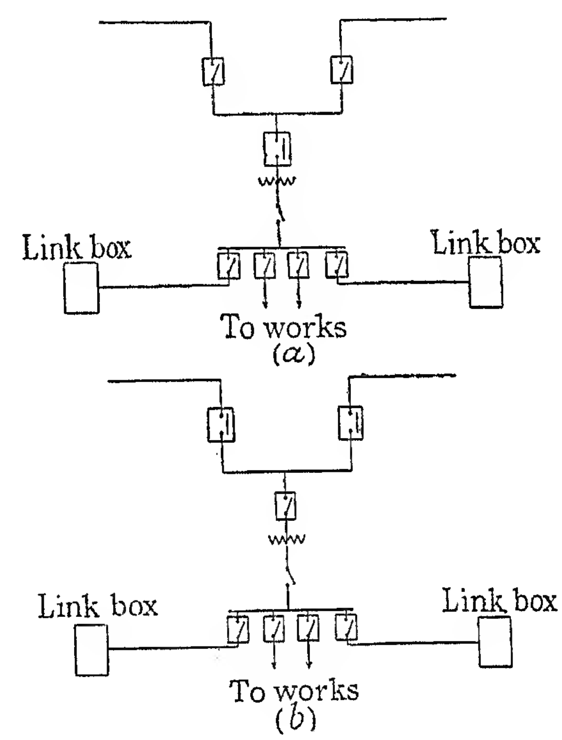

Fig. 18.—Switchgear for consumer's substation.

(15) MEDIUM-VOLTAGE APPARATUS AND CONNECTIONS

With 400/230-volt 3-phase 4-wire 50-cycle distribution, a loading density of about 20 000 kVA per square mile would seem to be the maximum which can be handled in city streets. For reasons of economy and voltage-drop, it is desirable to maintain the medium-voltage loading as far as is practicable below this saturation point, and to this end supply authorities should, wherever possible, endeavour to connect all concentrated blocks of load of reasonable size directly to the high-voltage network. Demands of 50 kVA and upwards may for this purpose be regarded as "concentrated blocks of load," and every effort should be made to induce such consumers to provide space on their premises for the reception of a high-voltage supply.

Two switchgear arrangements for controlling such supplies are shown in Fig. 18. It is suggested that these might be used alternately in providing supplies from a ring distributor; as if this method and suitable protective arrangements are employed a fault on the distributor

should only temporarily isolate one supply point. In Fig. 18, two medium-voltage cables are shown connected to street link-boxes. By means of these the consumer's substation may, if necessary or desirable, normally assist the general medium-voltage network; whilst, in the event of failure of the transformer, the feed could, by suitable linking, be reversed and a restricted supply given until a replacement had been effected. The remaining general supplies must be provided from the undertaker's substations, which will be disposed throughout the area so as to provide the emergency assistance indicated above.

In the principle of bringing the high-voltage supply as near as possible to the consumer's terminals would seem to lie the solution of a number of distribution problems in congested areas.

(16) VOLTAGE VARIATION

Apart from the duty of providing a supply within the statutory limits of voltage variation, the technical problem of voltage control is closely circumscribed by the hard facts of economics. Whilst technically it may be possible to work to any chosen degree of refinement, there is a limit below which it is not in the interest either of supplier or of consumer to go. The author does not subscribe to the view that elaborate methods and apparatus are necessary, on well-designed urban alternating-current networks, to preserve satisfactory regulation. The principle of bringing the high-voltage supply as close as possible to the consumers' terminals has already been enunciated, and not least among its advantages is the ensuing reduction in voltage variation.

A large proportion of urban load is of inherently high power factor, and consumers whose loads are outside this category should be offered financial inducements to fit power-factor-correcting equipment. Such consumers should be advised or constrained to improve the power factor, close to the seat of the low power factor, by means of apparatus which is switched in and out with the corrected plant. In this way the voltage-rise, and other undesirable phenomena attendant on leading power factor, at periods of light load, may be avoided.

Except in the case of very extensive networks, it is usually sufficient to regulate the voltage at the point of supply—by hand at attended power stations or automatically at unattended points.

To determine the required amount of regulation it is necessary to obtain simultaneous records of voltage at the point of supply and at a typical remote point on the high-voltage network. The difference between these records should be increased by a suitable percentage to determine the total variation referred to the high-voltage side, and the required voltage line at the point of supply is obtained by adding this total variation to the declared voltage. Should this resultant be found to impose too high a voltage on the alternators at maximum points, the general level may be reduced by introducing positive and negative variations about the declared voltage, the basic difference being made up by alteration to tappings on the distribution transformers. With hand regulation, any intricate form of curve may be followed if the attendants are vigilant, whilst, with automatic regulation, a similar effect may be obtained by influencing the voltage regulator by load current to provide the desired compounding characteristic.

Extensive networks are usually supplied from a superposed higher-voltage system, the unloading points of which constitute points of supply to the main network. Automatic voltage control of the type described at each of these step-down stations should therefore meet all normal requirements.

(17) CONCLUSION

This paper has been prompted by the author's experience in electricity supply work and contains a summary of some of the methods used, or to be used, in conducting the business of supply on a safe yet commercial basis. It is hoped that the technical approach to various general problems outlined herein may be of service to other engineers in their own specific problems, whilst the suggestions made, though by no means exhaustive, are intended to stimulate constructive thought on the major issues of supply work, some of which have become accentuated under interconnected working.

In accumulating this experience the author gratefully acknowledges the help and inspiration derived from the writings of others and the collaboration of colleagues. Some of the names of those to whom this debt of gratitude is owed are recorded in the accompanying Bibliography. The author also wishes to make special acknowledgment of the assistance received from Mr. G. A. Juhlin, who kindly supplied the information embodied in Fig. 6 and made many helpful suggestions. Thanks are also heartily accorded to Mr. J. Wylie for his invaluable assistance with the calculations and diagrams.

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[The discussion on this paper will be found on page 247.]

DISCUSSION BEFORE THE TRANSMISSION SECTION, 13TH JANUARY, 1937

Mr. H. A. Ratcliff: While restriking voltage is a very important factor in connection with switchgear operation, I suggest that arc energy is the factor which initiates the trouble in the switch and paves the way for the activities of the restriking voltage. In the days when switches were rather like tin cans with dangling contacts in them, the transient high-frequency voltage, which I suppose is more or less the same thing as the restriking voltage, had a way of manifesting itself across the terminals of the switch. When that was made a reason for endeavouring to get the standard length of terminal insulators and the clearances between them increased we were criticized, but it is very evident now that there was ample justification for calling for better clearances on switch terminals and associated insulators. These voltages, being of high frequency, sometimes cleared themselves without very much trouble or damage to the switch, but at other times they were followed up by low-frequency dynamic arcs. Even then the switch was frequently saved from destruction by the fact that the arc across its terminals brought out the master switch farther down the line.

In reading the paper I have been struck by the references to the magnitudes of the short-circuit currents, and I can hardly resist the conclusion that the author could very well do with some higher voltages on his system. Short-circuit values of 30 000 amperes or more are figures which largely disappear when higher voltages are employed. There should be some relationship between the main busbar voltage, the main transmission voltage, and the size of a system: the higher the capacity of a system, the higher the busbar and main transmission voltages. In other words, it is just as essential to have a high voltage for the transmission of large blocks of energy over a short distance as for the transmission of smaller blocks of energy over comparatively long distances.

The author deals fully with the subject of reactances, and there is no doubt that they have been an excellent panacea for many of the difficulties with which he has to contend. At the same time, I think it is inadvisable to flood a system indiscriminately with reactances. The correct place for reactances is, as the author shows in most of his sketches, between busbar sections, where the current flow through them is to a very large extent controllable; but even in such positions their indiscriminate use may at times lead to trouble, unless due precautions are taken when they are cut suddenly out of, or thrown into, the circuit. If it is necessary to have series reactances, it seems to me that the best way of introducing them is by installing transformers, and taking full advantage of the higher voltages thereby rendered available.

To touch on the debatable subject of efficiency and thermal capacity, in ordinary conditions, in a city of the size of London in particular, where one is concerned with laying transmission lines and distribution networks, the cost of the copper is such a comparatively small proportion of the total, and there are so many variables, known and unknown, that elaborate calculations regarding the economics of the subject are almost impossible. As regards the desirability of working cables up to the limits of their thermal capacity, in the case of low-voltage distribution networks this cannot be done in any case, because the voltage-drop would be excessive. In the case of 11-kV and 6-kV networks it can probably be done, but even then, if the distances are great, voltage-drop troubles may be experienced. With cables of higher voltage, the more the loading can be kept below the limit of thermal capacity the better.

The author mentions the desirability of using different sections of cable according to whether it is laid in the ground or in a duct. I have tried to do this in practice, but the problem becomes very involved, and sooner or later conditions arise which necessitate a last-minute decision to employ ducts. It is not possible in such circumstances to order a length of special cable and wait for it to be delivered. This is another reason why it is so desirable to adopt the practice of putting plenty of copper in the ground. If the suitability of a 0·2-sq. in. cable is in question, a 0·25-sq. in. cable should be installed. If this is done, the total cost of the job will then be very little more, but reliability and continuity of supply will be assured. An interesting fact which points to the desirability of having a good margin of copper is that in large cities the centre of gravity of the load frequently shifts. If there is not sufficient copper available to allow for change in the load distribution the necessity of putting down expensive additions at comparatively short notice may arise.

Turning to the subject of protective gear, I do not regard overload devices as fault protective gear in any sense of the term. Fault protective devices should be truly discriminative, and they should be as sensitive and instantaneous in action as possible, consistent with stability of the apparatus. What is equally important is that there must be entire freedom from inadvertent operation, the effect of which may be very serious. Discriminating protective devices must be selected with discretion and must be properly installed and maintained.

System stability is a field where overloads, and time-lags on those overloads, are of importance. On a large system fed by one or two interconnected stations and including a considerable amount of synchronous plant, when a fault occurs the synchronous machines can be held in step only by the passage between them of synchronizing currents of very considerable magnitude. Facilities must be provided to ensure that such currents are able to flow, and it is only by appropriate time-lag-on-overload devices, coupled with the use of instantaneous discriminating devices to clear faults, that it is possible to maintain continuity of supply.

The author's system of busbar protection is extremely simple but not very elastic, and it requires—though this is not apparent at first sight—very great care in its installation owing to the risk of casual earthing of the framework of the switchgear. The system employed by the undertaking with which I am associated is really a summation differential one in which all the incoming currents to the busbar and the outgoing currents are balanced, and the spill-over current, when there is a want of balance between incoming and outgoing currents due

to the existence of fault conditions, serves to actuate a relay. This arrangement is a little complicated, and requires care in its installation, but it has certain advantages. It gets over the difficulty which I have mentioned of the casual earthing of switchgear, and gives considerable latitude in the extent of the gear which is cut adrift in the event of a fault. At a big substation equipped with a number of switches it might be a serious matter to shut down the whole station in the event of a busbar fault, but with the arrangement to which I have referred it is possible to ensure that in the event of a fault only one busbar or busbar section is cut off. Such a scheme might well be applied in the case shown in Fig. 12, and would give a very large measure of flexibility and reliability.

I cannot tell from the paper whether the author has his neutral directly connected to earth or whether he earths it through a resistance. It is a great advantage if the general arrangement of the system can be such that in all probability any fault which develops will be a fault to earth rather than between phases; for then, if there is a suitable resistance in the neutral, it is possible to clear the fault instantaneously without any shock to the system and without taxing the switchgear in the slightest degree.

Mr. G. Rogers: The results of work at the three switchgear testing-stations now available in this country confirm the statement on page 229 that "there still remain aspects which are complex and obscure." A switch will pass all the tests and then, on a repeat test, it will for some unaccountable reason fail at a figure much less than its full rated capacity. Again, all too frequently in practice oil circuit-breakers are failing and causing serious fires and troubles up and down the country. Although they have passed all the recognized tests and are more or less of standard design, they fail at figures much less than their guaranteed maximum rating capacity.

I agree with the statement [Section (10)] "All circuit breakers should be remotely operated," but unfortunately there are many types of switchgear in use, particularly of the cellular type, with which it is very difficult to have remote operation. In such cases I would go further than the author and say that all switchgear of a rated capacity of, say, over 150 000 kVA should be closed by electrical or pneumatic means or by spring control. Spring control is a comparatively new method and is an arrangement which enables the switch to be closed by the operation of a powerful spring. Remote operation in the sense intended by the author has, I suppose, special reference to the safety of the operator. In the cellular type of gear to which I have referred, where the operating handle is situated just in front of the cubicle, there is generally a sufficiently strong steel plate in front of the panel to safeguard the operator, provided the switch has not been called upon to break more than its rated capacity.

The author devotes a considerable amount of space to dealing with voltage decrement and also with the decrement in the recovery voltage. I believe it is the general practice, when calculating the short-circuit kVA at any point of a system, to ignore the question of voltage decrement, and for general practical work I think it is advisable to ignore all questions of alternator voltage-decrement and to calculate the short-circuit kVA on the basis of the full voltage and full recovery voltage. Further, I would say that the rating of all e.h.t. switches should be in excess of the calculated short-circuit kVA with which they may have to deal. In the undertaking in which I am interested no switches are allowed on the e.h.t. system which have a breaking capacity of less than 150 000 kVA. This may seem rather unnecessary if the calculated short-circuit kVA is of the order of 70 000 or 75 000, but the difference in cost is very small, and it is not worth while putting in switches of 75 000, 100 000, or 125 000 kVA breaking-capacity to save a small sum. Larger switches are used, of course, where the concentration of power is greater, and standards of 250 000, 350 000, 500 000, and 1 500 000 kVA would seem to be a very reasonable range to be used on any one system.

At the end of Section (10)(*a*) the author says "The discovery of a satisfactory insulating fluid of a non-combustible nature for use in circuit-breaker enclosures would also be a contribution to continuity of supply." Arising out of this, I should like to draw attention to the fact that abroad oil-less circuit-breakers are being used to a considerable extent. I refer, of course, to circuit breakers of the air-blast type. These have been developed up to the maximum sizes that are required, i.e. up to 1 500 000 kVA, and have, I understand, been found to be more or less satisfactory in service. Manufacturers in this country seem very loath to pursue inquiries into the air-blast type of circuit breaker; is this because they fear or know that the principle of this type of switch is fundamentally wrong? A strong feeling is arising among many engineers in this country in favour of oil-less circuit-breakers, and it would be very unfortunate if they had to go abroad to purchase switches of this type.

In Fig. 11 the author gives a diagram of connections of the switchgear layout of generating stations. Fig. 11(*c*) may be said to represent the conventional type of layout, as this is the one which has been or is being adopted by almost all the large undertakings in this country. It is very convenient and satisfactory, particularly as it is now possible to incorporate in it satisfactory busbar protection. Another type of layout which has been talked about a great deal lately is known as the mesh system of connection. This system consists of a busbar ring, the switches all being in series. It requires fewer circuit breakers for a given number of circuits than the conventional type, and has the further advantage that it lends itself very readily to busbar protection. On the other hand, it appears to me to introduce very serious operating difficulties. I should be grateful if the author would give us his views on this system.

With regard to voltage regulation, my experience confirms the author's view that, generally speaking, satisfactory regulation can be obtained at the source by hand operation, usually, of course, in the form of transformer on-load tap-changing gear. Nevertheless, in outlying areas where small static substations of the type referred to in the paper supply the local demand, I have found automatic on-load tap-changing gear very satisfactory when applied to small transformers up to 500 kVA capacity. Such automatic gear can now be obtained at a very reasonable price from most of our transformer manufacturers.

Mr. D. E. Bird: The author does not refer in great detail to the question of circuit closing. The power taken to close solenoid-operated switches is very considerable, and I feel that 150 000 kVA at 11 000 volts is the upper limit for manual operation. Most of the switchgear faults that I know of which have occurred in recent years have resulted from the slow closing of a circuit breaker by hand. I think that manufacturers would do a service to the industry if they would conduct a series of experiments on the power which can be successfully "made" by hand on any given switch.

The author mentions a system of busbar protection, and in the discussion what seems to be a very complicated system has been elaborated; but no one has yet suggested the earthing of the system through a Petersen coil or arcing-earth suppressor. It seems to me that earthing the neutral in that way solves a great many of our problems. Not only does it afford earth-fault protection to the switchgear, which is really the only type of busbar fault likely to occur, but it protects the network, whether it be a cable network or an overhead system, and also enormously improves continuity of supply. On one overhead network of considerable length of which I have had experience, in 12 months there was a total of 27 faults. Of those, 24 were dealt with by the Petersen coil without any interruption to the supply. In one instance the fault was due to a spike driven into a cable by a gang of navvies repairing the road, and as in this case the cable was the only one supplying a power consumer, the fault was left on for several hours, until the factory had shut down and the supply could be cut off without inconveniencing the consumer. The drawback of the Petersen coil which is often referred to is the question of tuning. A great number of experiments has been made in regard to the accuracy of tuning required for a Petersen coil, and it has been found that the coil can be a very long way out of tune without affecting the results, particularly on lower-voltage networks. With 11-kV systems, for example, if the coil is 25 or 30 per cent out of tune it does not really matter. Splitting up the network and cutting pieces off for repairs does not as a rule involve the retuning of the coil.

The author refers in Section (10)(*b*) to the system employing a master switch with smaller feeder switches in series. I should like to know whether he considers this a good system for a new layout or whether he proposes its adoption only to get over the difficulty of increased short-circuit capacity of the system and of making use of existing switchgear of small rupturing capacity.

[The author's reply to this discussion will be found on page 253.]

SCOTTISH CENTRE, AT GLASGOW, 12TH JANUARY, 1937

Mr. H. M. Stronach: In my opinion the most important point made by the author occurs in Section (15) where he states "a loading density of about 20 000 kVA per square mile would seem to be the maximum which can be handled by medium-voltage systems in city streets." I am in entire agreement with this view, and I would ask those who have any doubts in this connection to visualize low-voltage supply to districts $\frac{1}{4}$ square mile in area with an existing load density of over 100 000 kVA per square mile and no indication of saturation. Many undertakings are to-day substituting a.c. supply for d.c. supply, and I would point out that the advantages of change from a medium-voltage d.c. to a medium voltage a.c. system, with load densities such as those indicated above, are very doubtful. Concentrated blocks of load of 50 kVA and upwards must be connected direct to a higher-voltage network, and individual consumers or proprietors of property where the future load is likely to reach this figure must provide space to enable such a supply to be afforded. No medium-voltage service cable larger than 0·06-sq. in. cross-section should be led into a consumer's premises within this loading danger zone. A definite policy in this connection will decide the medium-voltage cable layout, the secondary high-voltage network layout, and also how far these should conform to the principles laid down in the paper.

Mr. A. P. Robertson: I am not altogether in favour of the control-circuit layout shown in Fig. 13, as I think that there is a possibility of the relays controlling the master switch giving trouble. The idea of a large switch breaking an initial fault and allowing a smaller switch to open its own circuit is certainly very good, and, if it were certain to operate, it would be almost perfect; but this method of opening circuits and working on relays has been applied to transformers for tap-changing, and has been found to involve the possibility of one of the breakers sticking occasionally and throwing the full load on to one winding of the transformer. The same thing might occur in this case. If the feeders shown in Fig. 14 were fully loaded, and if the master switch did not close again as it ought to, then some feeders would be left with a considerable overload, and some of the results we have seen indicate that this might be dangerous. I think that a simpler method would possess greater advantages in operation.

Fig. 11 shows four different layouts, each with its own particular advantages. I rather like (*c*) and (*d*). Layout (*d*) has the advantage that fewer large switches are required on the main busbars and that smaller-duty switches can be used for the feeders. If the reactors are suitably designed I think that to a great extent the voltage-regulation troubles can be overcome. Layout (*c*) is more detailed, and lends itself very well to the system of isolation of switches shown in Fig. 12.

The segregation of switchgear is now receiving a great deal of attention. I am not sure that it is absolutely necessary to have the switchgear in separate buildings, if good walls are put up between the sections: it is of no use having $4\frac{1}{2}$-in. walls, as is suggested in some cases, since an explosion would soon put these out of action. Busbar protection is being considered by many people nowadays. I think that the system shown by the author of insulating the main switchboard is inadvisable, as it does away with the ironclad idea. No part is fully earthed, and also it is difficult to keep the insulation perfect. If the switchgear is mounted on insulating material which is close to the floor, that insulation soon deteriorates in consequence of the dirt and dust, which

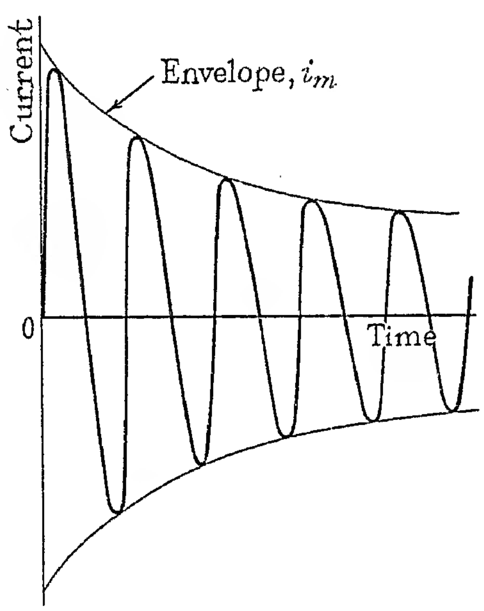
cannot be kept away. Trouble of this sort has occurred in connection with rotary-convertor bearings, with the pedestals insulated at one end.

Continuity of supply to works and other consumers is very necessary, and I am in favour of the arrangements shown in Fig. 17. The trouble about the protection of transformers and other apparatus is that it requires, where the load is concentrated, very heavy switchgear, and the space factor is of great moment. The switchgear may take up more than half the space of any small substation. I think that if some other method of protection could be devised it would go a long way towards making substations for 50 or 100 kVA a practical proposition. This is one of the great difficulties which engineers are up against at the present time. If these other matters are taken into account beforehand, I think it will be a long time before voltage regulations will be actually required on the supply network.

Power-factor-correction devices give a great deal of trouble, because some consumers have a condenser on the main supply which they switch out at night and forget to switch in again in the morning, and this causes serious interference with the maximum demand. On the other hand, if a large condenser is left in circuit the voltage is raised, with the result that the life of lamps is shortened. The correct method is either to have the condenser controlled by the main switch or to employ a separate condenser for each motor.

Prof. M. G. Say: A fault current may be symmetrical or otherwise according as the envelope of its wave-form is or is not symmetrical about the time axis. A fault may be symmetrical or otherwise according as it affects all three phases equally or not. On page 230 it is not, I think, always quite clear which symmetry is referred to: compare, for instance, the legend to and the description of Fig. 2. While the paper is certainly not the place in which to deal exhaustively with fault-current phenomena, some mention might have been made of currents due to unsymmetrical faults. They are liable to occur more frequently than symmetrical 3-phase faults, and the currents involved may be greater. The analysis of such cases is not straightforward, but the method of symmetrical co-ordinates and the idea of transient and sub-transient reactance have enabled calculations of the fault current to be successfully made.

It is readily possible to find the transient and sub-transient reactances from an oscillogram of a symmetrical current wave-form. The envelope is plotted with logarithmic ordinates to a base of time. The result is a line, substantially straight except in the region near the axis of zero time (i.e. immediately after the initiation of the fault). Extrapolation of the rectilinear part back to the ordinate-axis enables the reactances X' and X'' to be found (see Fig. A). An estimate of the time-constants can also be made.



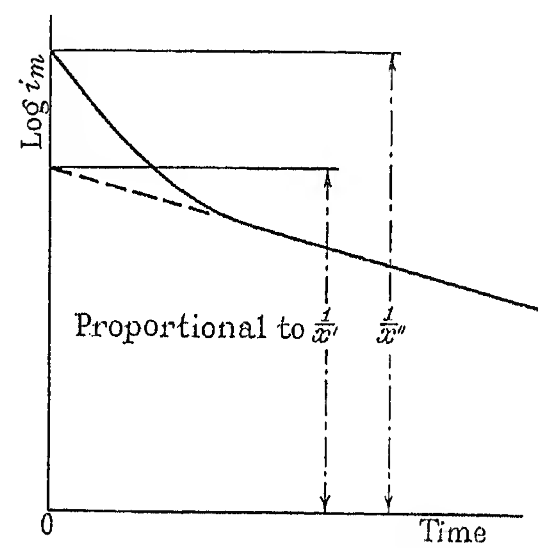


Fig. A

Mr. A. E. Kelly: Referring to page 240, I should like to ask the author whether he has found the system of delayed operation, as outlined under the heading "Economic Considerations," to work to his satisfaction under fault conditions.

The various layouts of substation equipment shown in Fig. 17 are interesting. The question of complete protection and continuity of supply, it seems to me, is decided to a large extent by the capital expenditure one can justify for the particular job in hand, and also by the size of substation.

Dealing with the question of transformer noise, I cannot agree with the author that a great deal of improvement has been obtained in the diminution of noise in consequence of a decrease of flux density.

Mr. G. Henderson: In referring to the case illustrated in Fig. 6 the author said that the fault would be cleared in 0·2 sec., i.e. 10 cycles, but if one examines the short-circuit oscillogram one finds that in 10 cycles the current has fallen to a much lower value than the instantaneous short-circuit current, which means that the switchgear is clearing on a fault kVA, not the value as calculated from instantaneous figures. In this case the machine or transformer has to be designed to withstand the full mechanical forces on short-circuit for a longer period than if the switchgear were designed to open in, say, 5 cycles, and so it should be borne in mind that the speed-up in tripping time imposes more severe conditions on the switchgear.

I am a believer in setting overload relays for instantaneous tripping, but for a current value in excess of

the overload rating of the plant to be protected, so ensuring that this instantaneous tripping only occurs under fault conditions. If possible, a further relay should be fitted with tripping settings corresponding to the true overload rating of the plant being protected, thus avoiding the all-important overheating if the overload should be carried for an excessive time.

The author mentions the fact that if busbar condensers installed for power-factor correction are left in circuit when the motors are shut down, the result is an objectionable voltage-rise. Does this mean that he would prefer to have a condenser to each motor, with a common switch controlling both?

I was interested in the voltage-regulation curve shown by the author, and would ask him to state whether the regulation at the domestic consumer's terminals is as good as that obtained at the substation.

Mr. E. Seddon: I frequently ask myself "Where is this continual demand for larger switchgear leading us?" The interconnection of large power plants has not lessened our anxiety in this respect, and switchgear purchased to-day may become too small in a few years' time, as power sources are added. Manufacturers are stiffening their prices for switchgear to such an extent that we shall soon be compelled to consider other, more economical, means of controlling our circuits. The present price of a metalclad switch of 1 500 000 kVA rupturing capacity with electrically-operated isolating switches for duplicate busbars, suitable for a 30 000-kW turbo-alternator and insulated for 6 600 volts, is between £8 000 and £9 000, and this is becoming a serious item in generation capital costs. I should like to ask the author whether he considers any economy would result from the use of short-circuited reactors which would be introduced into the circuit on the opening of a switch, the final break being taken on a smaller circuit breaker than would be necessary for interrupting the maximum fault current. I should also like to know whether British manufacturers have made any progress in the direction of oil-less switchgear, as I understand this type of gear has been used successfully in Germany for many years.

On page 245, under the heading "Transformers," the first paragraph is a little difficult to understand. Does the author consider that the ideal system should provide for the whole load of a substation being taken over by the low-voltage cables of adjoining substations in cases of emergency? If so, this would seem to imply an unnecessary and extravagant use of copper.

Mr. D. Martin: The case referred to as an instance of what is regarded as a high price demanded by the manufacturers of switchgear is £8 400 for a 3-phase 6 500-volt 50-cycle compound-filled, metalclad switch having an oil-immersed circuit breaker, for use with the new 50 000-kW turbo-alternator at Portobello power house. If 50 000 kW was the total power to be controlled by that switch, then I would agree that there would be some reason for complaint. Taken alone, and allowing approximately 10 per cent reactance in the alternator, the duty would be roughly 500 000 kVA for short-circuit fault conditions in the circuit external to the machine. But that is not all, for the author has indicated that the plant capacity at Portobello, without this new alternator, is something like 75 000 kW, which would add a further 750 000 kVA, making 1 250 000 kVA in all. In addition to this there is the grid connection on the busbars at Portobello—an unknown quantity, dependent upon the plant capacity of the other power stations such as Bonnybridge, Clydesmill, Dalmarnock, Yoker, and the hydro-electric sources of the Grampians and Galloway schemes, which may be running in parallel with the Portobello plant. The figure specified by the engineer, to the switch maker, as the rupturing capacity which the switch must clear under fault conditions without injury to itself or the plant which it controls, is 1 500 000 kVA. A simple calculation will show that this means that approximately 69 000 000 000 ft. lb. of energy must be dissipated at the switch contacts in a fraction of a second. The switch maker has already built switchgear suitable for this duty.

The author gives a clue to the problem on page 238, where he says "The electromagnetic force . . . varies as the square of the instantaneous current." From this it is obvious that the circuit breaker must be capable of dissipating the energy developed at the moment of fault and it must also be so substantially made that it can withstand the enormous electromagnetic forces developed. I have seen a bronze plate, measuring roughly 24 in. by 24 in. by $1\frac{1}{4}$ in. thick, buckled by as much as 1 in. out of truth; and again, a 9-in. diameter steel baffle plate, 1 in. thick, with some fifty $\frac{3}{8}$-in. diameter holes drilled in it, buckled as much as $\frac{3}{4}$ in. out of truth, by the forces met with in switch operation.

In 1928 the first British switchgear short-circuit test plant was laid down at Hebburn, at considerable expense. This proving plant showed that, while the switch maker was on the right lines, constructional details had to be improved if safety was to be preserved. Another factor contributing to the present position in regard to switchgear prices relates to labour costs, which have risen in consequence of the shorter working week and subsequent wages advances. There is also the increased cost of materials and power, arising out of Government pressure to stabilize a better wage for the miner. In spite of all these factors tending to send up prices, the present (1937) figure of £8 400 for a 1 500 000-kVA switch compares favourably with the 1920 figure of £2 000 or £3 000 for a switch of the order of 250 000 kVA. The conclusion is that, while the duty has increased in the ratio 36 : 1 (in the proportion of the square of the current concerned), the price has only advanced in the ratio 4·2 : 1. Comparing these figures with the recently-published prices of another piece of apparatus, namely power transformers, we find in the latter case a power ratio of 1 : 25 and a corresponding price ratio of 1 : 10. This example helps to show that the switch maker, while building to a specification, is doing his best to keep the price at a minimum.

If the supply engineer thinks switches are too dear he has the remedy in his own hands. It is he who specifies the duty, and if he will reduce the duty in his network plans, at switching points, as indicated by the author, then there will be some hope of keeping down the amount required for switchgear. The whole problem is one of finding a happy medium in distribution.

Happenings during recent months have pointed to

the desirability of limiting power on low-voltage network systems to about 60 000 kVA. This, in turn, has meant the regrouping of supplies and the more frequent use of busbar sectionalizing in ring-main systems, which, after all, is the most economical layout. Going farther back, to the point of supply, the number of groups is a matter for individual consideration, but grouping here, with the larger power now available, seems inevitable from the continuity-of-supply point of view alone, if one wants to reduce complicated protective systems to a minimum. Recent practice also shows it to be more economical on a large network to run the e.h.t. supply as near as possible to the consumer's terminals, in order to avoid voltage variations.

In conclusion, I notice that the Bibliography omits to mention the valuable papers on this subject published in the *Journal* during the past 30 years by Mr. H. W. Clothier. These are embodied in "Switchgear Stages," a work which I can recommend.

[The author's reply to this discussion will be found on page 253.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT CHESTER, 23RD FEBRUARY, 1937

Mr. W. Fennell: The question that has been worrying me a good deal lately is to fix what may be called an "upper limit" for the output in a certain area. Very naturally we have laid out the system to meet what appear to be the more immediate needs, not only in circuit breakers but in the general layout of the feeders, and find generally that the usually-adopted voltages are too low. I had some inkling of what might happen as to load when dealing with Mid-Cheshire 12 years ago, and consequently adopted 33 000 volts in the main layout. We have never regretted doing this, but with the more recent complications of connecting to the grid system, and applying these new connections to the old arrangements, I have a feeling that we are trying to put new wine into old bottles.

One of the developments that I have supported for a good many years is bringing the high-voltage supply close up to the consumer's terminals, and a good portion of my Chairman's Address to the Transmission Section* was devoted to this subject. I felt justified in my view when I heard the present author predicting what is going to happen in the future.

I advocate very strongly the remote operation of all important switchgear, and especially that which has been installed in the older stations or is being altered to comply with grid conditions. It is a disturbing thought that when a switch is closed the person putting it in may be exposed to the devastating effects of oil explosions.

With regard to Fig. 15, dealing with the short-circuit temperatures of cables, the indicated risk of injury to the cables is incredible, because almost all of us have experience of large momentary currents being carried on small cables without causing injury. It may be that the temperatures which paper cables will stand for short periods has been under-rated. If the author's figures are correct I heartily endorse the suggestion that cable boxes form splendid safety-valves. I would also advocate the continuance of the system of making the spindles small so that they could act as fuses and protect the cables if an over-rated circuit breaker failed to open on a short-circuit.

Mr. A. N. Mansfield: On page 237 the author refers to 0·1 sec. as the time-interval for the operating of a switch. I suggest that this period is rather short and is not attained by the average breaker. I understand that 0·2 sec. or a little more is the usual figure for the sort of switch employed on a supply network, and I suggest that this longer interval would be more suitable for use when calculating the short-circuit values. The greater decrement factor would then be utilized and a more accurate forecast of the conditions obtained.

The arrangement of the master breaker controlling groups of feeders shown in Fig. 13 calls for the master switch to trip on every occasion, irrespective of the nature or severity of the fault. A system on which this could be tolerated would have to be unusually elaborate. A layout using lock-in relays on the feeder switches set to a kVA value within the capacity of these switches would probably have a far wider application.

Turning to the provision of transformers for substations (page 245), the governing factors set out by the author are those of loading and relative importance of the substation. In practice, however, the questions of accessibility of site and of transport sometimes have to be considered. In North Wales, for example, we have substations located in all sorts of difficult places, sometimes at quite high altitudes, and we have to keep standby units available, quite apart from those necessitated by loading conditions. With the greatly increased numbers of substations now required it is possible for awkward situations to occur even in towns.

Mr. W. F. Sands: The author appears to base his conclusions on data obtained from an existing system, and it seems to me that he has stopped short of the final solution to the problem. Apparatus, particularly switchgear and cables, has to be installed, not to meet the conditions which exist at the time it is being installed, but those which are going to exist immediately prior to the time when the apparatus is to be taken out of service. After arriving at the rating of apparatus in the way outlined in the paper, it becomes necessary to apply some factor to allow for the expansion of the system during the working life of the apparatus; it would be interesting to know on what basis the author has arrived at that factor. He has mentioned that the system with which he is associated now has a capacity of some 75 000 kVA, but if he has installed switchgear recently it would be interesting to know what ultimate capacity he has allowed for.

It is perhaps inevitable in the present stage of progress in the electricity supply industry for the problem of short-circuits to be tackled in the way adopted in the paper, by providing apparatus of sufficient capacity to carry and/or rupture the current involved. It seems to me, however, that with the continued growth of systems and of the

* *Journal I.E.E.*, 1936, vol. 78, p. 18.

short-circuit kVA which can be released through a fault, it will become impossible to continue to increase the rating of apparatus to deal with such conditions, and more attention will have to be paid to prevention rather than cure. Most short-circuits are the result of a failure of insulation, which in the majority of cases does not take place instantaneously but is the result of deterioration over a period of time. Greater attention will have to be paid to detecting this deterioration before a severe short-circuit takes place. Already transformers can be fitted with the Buchholz relay, which gives an indication of incipient faults. In the case of high-voltage cables a technique of d.c. testing is now being developed whereby it is possible to locate faults which are developing and to effect repairs before the cables break down while in service and cause a major disturbance to the system. Serious trouble can also be experienced through the breakdown of insulation in switchgear, and it seems quite practicable to provide some detecting device which will indicate when deterioration of the insulation is taking place.

Referring to the title of the paper, a new meaning seems to be creeping into the word "rating." At one time "rating" conveyed the normal duty which the gear was called upon to perform, but nowadays it seems to refer to the abnormal duty, and the paper illustrates the tendency for the abnormal duty to have the major influence on design. The point I wish to make is that, although at the present time the design of systems and the rating of apparatus must provide for the abnormal conditions which occur during short-circuit, this state of affairs cannot go on indefinitely, and attention should be paid to evolving methods to ensure that a major breakdown becomes a rare occurrence and not a major influence in the rating of apparatus.

Mr. S. E. Britton: Some 15 years ago we put in switchgear designed for a rupturing capacity of 50 000 kVA, and we thought that this was of the best possible design. We soon learned, however, that it ought to be de-rated, and to-day we are told that, owing to the growth in the supply and its connection to the grid, we should scrap the whole of that switchgear and adopt apparatus with not less than 250 000 kVA rupturing capacity. We have to realize that 15 years ago, with their limited knowledge of rupturing capacity and the effects of surges due to the capacity of generating stations and extensive interconnected networks, switchgear manufacturers had not sufficient practical information for guidance. To-day we are in a somewhat superior position due to more thorough research and the facilities manufacturers have for testing apparatus to destruction.

I am not one of those who thinks we should aim at 100 per cent continuity of supply; to me it is a question of commercial value and commercial risk. What we want is apparatus which enables us to get a supply of electricity for all purposes which can be economically applied to present-day requirements.

Mr. M. N. Humphreys: I should like to raise the question of the easement of the duty on a circuit breaker due to a fault coming on gradually. The fault may reach its greatest value when the contacts are just parting, and if this happens conditions are worse than they are when one is testing circuit breakers. When a breaking-capacity test is being made on a circuit breaker, the test breaker may be tripped out before the circuit breaker initiating the short-circuit current has closed; but one has to have a certain overlap between the two events, and there must therefore be a certain time during which the decrement of the circuit takes effect. If a breaker in service has to get any advantage from a fault coming on gradually, it must be tripped out before the fault has reached its maximum value, but one cannot rely on the tripping gear operating in such a time that the circuit will be opened under favourable conditions.

I cannot agree that the presence of large induction motors should be taken into account in estimating the maximum short-circuit power which can be fed into a system, since, apart from the fact that an induction motor can only feed back by virtue of the residual field, if a motor were running with 5 per cent slip when a fault occurred on the system the motor volts would be out of phase in 0·2 sec., i.e. in approximately the time of tripping and opening of a circuit breaker.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, GLASGOW, AND LIVERPOOL

Mr. J. Eccles (*in reply*): The discussion on this paper falls into four divisions—agreement, disagreement, constructive suggestions, and questions, and the reply will deal only with the last three. Where a point has been raised by more than one speaker a collective reply will be given, and speakers' names will only be mentioned where individual replies are necessary.

Several speakers have made the point that the design of systems and apparatus should be based on ultimate output and ultimate power concentration. Theoretically this is incontestable, but even if these ultimate values were known such a procedure might be financially impossible in the early stages of development. The art of system design is to so fashion the layout that all the components will fit into the larger framework which load development will produce. A bold decision in the selection of the primary transmission voltage is essential and in no case should this be less than 6·6 kV. For urban systems in this country the following formula gives satisfactory results above 6·6 kV:—

$$\text{Minimum system voltage} = \tfrac{1}{30}\left\{\begin{array}{l}\text{Estimated ultimate output (in kVA)} \times \\ \text{Transmission distance to centre of gravity of} \\ \text{load (miles).}\end{array}\right.$$

The art of applying such a formula lies in the accuracy with which the variables are estimated. In practice what usually happens is that the system voltage is increased with output through the superposition of a higher-voltage network when transmission difficulties become serious. It is wise to anticipate limitations due to low transmission voltage by superposing the higher-voltage system in advance of necessity. Switchgear at the point of supply should be designed for the ultimate power concentration, but more caution can be exercised

in the rating of apparatus on the network, as by utilizing some of the methods outlined in the paper the power concentration at any one such point may be kept within predetermined limits whatever the generating plant capacity may be. Perhaps the most important fact for distribution engineers to realize is that network power concentration must be limited to values which can be controlled by reasonably priced switchgear rather than switchgear costs piled up in an attempt to control unlimited concentrations.

The group control scheme outlined in the paper was adopted as an economic solution to a switching problem where the power concentration was high. The master switches existed and the low-rupturing-capacity feeder switches were specially designed for the duty. It would be unwise to use normal light-duty switchgear for this service, because of the heavy fault currents which must be carried before the master switch opens. Whatever scheme of protection is used it is impossible to ensure that a fault will not develop beyond the rupturing ability of the feeder switch, between the instant that the relay energizes the trip coil and the final interruption of the arc. Because of this limiting feature it was decided that the master switch should operate on all faults. The risk of mal-operation is minimized if careful attention is paid to the design and installation of relays, if the control room is kept warm and dry, and if routine operation tests are made at regular intervals.

The reason for the selection of the 0·1-sec. point on the decrement curve for calculating switchgear duty is given in the paper, and the fact that the average operating time of normal circuit breakers is 0·2 sec. is also stated. The calculation based on the shorter time gives a higher duty for a given curve and allows a factor for unusual or inadvertent operation. Time delays in circuit breaker operation tend to ease the rupturing duty but increase the thermal and physical stresses in the protected plant and cables. The disadvantages of time-lags outweigh the advantages, and for this reason instantaneous protection is advocated in the paper.

I heartily endorse the suggestion that all circuit breakers rated above 150 MVA rupturing capacity should be arranged for remote closing. A spring closing mechanism is now made by various manufacturers and in many cases offers an economic solution to this problem.

Oil-less switchgear has thus far not found favour with British manufacturers, possibly owing to patent difficulties and to the cost of departing from standard tried designs. In the matter of limiting the consequences of oil fires it is felt that much could be done, without forsaking the oil-immersed principle, by insulating the tank internally for the full circuit voltage and employing a relatively small quantity of oil for arc extinction.

There are limitations to all forms of busbar protection, and after reviewing all known types I decided that, on balance, the frame-leakage scheme was best suited to my system. A weakness of the differential-leakage-current type is that the final number of feeders and their current-transformer ratios must be decided in advance; otherwise the summation transformer will require modification each time a feeder is added. It is a mistake to suggest that with frame-leakage protection the switchgear framework is insulated from earth, as the substation earth plate is the only reliable "earth" and the efficiency of this connection is unimpaired by the fact that it also acts as the primary of a bar-type current transformer. A switchboard so protected is readily extensible without alteration to the protective gear, and individual protection for sections of a switchboard such as is shown in Fig. 12 has been easily and satisfactorily obtained.

I agree with Mr. Ratcliff that the use of reactances must be judicious. After one or two unsuccessful experiments I have ruled out the use of series reactances at the point of supply. The method of varying the section of a cable according to whether it is laid in the ground or in ducts has been confined to main feeders. Here the route is determined well in advance of the installation date, the length of available ducts is known, and there is little likelihood of the cable being cut into at a later date to supply an intermediate substation. Under these conditions the method has shown a saving in total costs per ampere transmitted. My system is earthed through a limiting resistance.

Mr. Rogers raises the question of delta versus star connection of busbars. The delta connection sometimes permits of a reduction in number of circuit breakers for a given number of circuits, and where the total number of circuits is small the method is practicable. Where it is desired to provide intersection reactors controlled and bypassed by circuit breakers there is no saving in switchgear as compared with the equivalent star arrangement. For example, a delta arrangement to give the same flexibility and standby connections as that shown in Fig. 11(*c*) would not be less expensive and would be more complicated physically.

I thank Mr. Bird for valuable particulars of his operating experience with Petersen arcing-earth suppressors. These devices have not yet been employed on urban systems in this country, but in other European countries I understand they have been so used. The capacitance of a high-voltage cable network is such that the coil for a moderate network is bulky and somewhat expensive. On overhead systems, which seem to be more suited to this form of protection, it is important to remember that each phase conductor must be insulated from earth for full circuit voltage. Spill-over insulators must be removed, and experience seems to be inconclusive as to the effect of this change on the damage caused to the line and connected apparatus by a direct lighting stroke. Nevertheless, if suitable precautions are taken this form of protection should be of great value in preserving continuity of supply on rural networks.

Mr. Robertson's point regarding the cost and size of switchgear for controlling a 50- or 100-kVA high-voltage supply to a consumer is very pertinent, and manufacturers with full-scale testing facilities might with advantage develop a range of reliable switch fuses for this service.

In reply to Prof. Say, Fig. 2 deals with a single-phase circuit in which only the fault current can be asymmetrical. Unsymmetrical 3-phase faults were not dealt with in the paper, owing to lack of space and to the fact that in practice the great majority of these have proved to be faults to earth which, in most systems in Great Britain, are limited by neutral-point resistances and therefore do not impose a heavy duty on the switchgear.

As shown by Prof. Say in Fig. A, it is relatively easy to deduce the sub-transient and transient reactances from an oscillogram of short-circuit current, and I thank him for drawing attention to the method employed.

Mr. Kelly's experience differs from mine in the matter of diminution of transformer noise through decreasing the flux density. Ordinary core-type transformers are certainly less noisy at lower densities, but there is one special design of transformer in which the noise level is low at normal destinies, and perhaps it is to this type that Mr. Kelly refers.

Regarding Mr. Henderson's remarks on the proper point to connect condensers for power-factor correction, I would refer him to Mr. Robertson's contribution to the discussion on this subject, with which I am in agreement.

I sympathize with Mr. Seddon in his complaint regarding the cost of heavy-duty circuit breakers, but the fact that such units are few in number and that the price is controlled seems to rule out any prospect of reduction in cost. In this connection Mr. Martin makes the sound point that the best way to reduce circuit-breaker costs is to reduce the power concentration they will be called upon to interrupt. In my view, the use of reactors which are normally short-circuited would not show any saving over the group-control scheme outlined in the paper. The paragraph on transformers referred to by Mr. Seddon is intended to be an argument in favour of multi-transformer substations. It seems doubtful, even in densely loaded areas, if one substation could be relieved of the whole of its load by adjacent substations. Although the substations are closer together their individual loading is greater than those of substations in less densely-loaded districts, and the problem of load transfer may not be greatly different for the two cases.

Mr. Martin makes out a strong case in justification of switchgear prices, but to be strictly accurate it requires to be stated that the installation of a generator of the size he mentions is not contemplated in the power station referred to.

Replying to Mr. Fennell I find no reason to doubt the accuracy of the temperature/time curves shown in Fig. 15 for the postulated conditions, and the fact that light cables have been known to carry heavy transient currents without any immediately apparent injury serves only to show either that paper insulation can successfully withstand high temperatures for short periods, or that the damage sustained is insufficient to cause immediate failure of the cable. His suggestion that leading-in stems should act as fuses will, I trust, not meet with general approval.

I am in complete agreement with Mr. Sands when he suggests that deterioration should, where practicable, be detected and faults thereby anticipated. On systems operating at 11 kV and over, d.c. pressure-testing of main cables should be a regular routine. The infrequency of faults on 6·6-kV cables, and the smaller kVA transmitted per cable, render the wisdom of such testing more problematic on systems operating at this voltage. In any event one can scarcely hope to anticipate all faults, and the day seems far distant when the design and rating of circuit breakers will not be governed by the conditions which occur during short-circuits.

In reply to Mr. Humphreys, the easement in switch work through the gradual application of a fault was intended to refer more particularly to power-station switchgear. To take an extreme case, if an alternator is overloaded by small increments until the external impedance becomes zero the current at any stage will not approach the value which would have been attained had a short-circuit been instantaneously applied to the same machine. Network faults exhibit the same characteristics, though to a lesser degree.

Induction motors driving d.c. generators in substations adjacent to the point of fault do contribute to the fault current, by virtue of the a.c. excitation and the stored energy of the d.c. system.

THE METERING OF MERCURY-ARC RECTIFIER SUPPLIES AND OUTPUTS

By C. DANNATT, D.Sc., Member.

(*Paper first received* 30*th September*, 1935, *and in final form* 27*th August*, 1936; *read before the* METER AND INSTRUMENT SECTION 5*th March, and before the* NORTH-WESTERN CENTRE 6*th April*, 1937.)

SUMMARY

A preliminary survey is made of the difficulties involved in metering (*a*) active energy, wattless kVA, total kVA, and power factor, in the input circuits of mercury-arc rectifiers, owing to the presence of harmonics in current and voltage; and (*b*) energy output from mercury-arc rectifiers when considerable ripple exists in the current and voltage.

The performance of induction-type and motor-type integrating meters is then examined experimentally on rectifier circuits, and the observed errors are quoted. Good agreement is found between the observed errors and those expected from theory and the known variation of the meter characteristics with frequency, both in the case of energy and in the case of kVA measurement. Similar tests are described on motor- and mercury-type integrating meters on the output side of rectifiers.

It is concluded that a.c. power measurements can be made with satisfactory accuracy by induction- and motor-type meters. No entirely satisfactory solution is found, however, for power-factor and kVA measurement. Finally, the necessary precautions to be taken with d.c. integrating meters on the output side are dealt with.

(1) INTRODUCTION

The introduction of mercury-arc rectifiers into supply-system loads has brought with it difficulties associated with the metering of the energy supplied. They arise from the fact that the current, and in certain cases the voltage, are considerably distorted, whereas the meters used for measuring active and reactive energy are frequently so designed that they function accurately only when dealing with sinusoidal quantities of fundamental frequency. Errors are liable to arise, therefore, in the first place owing to variation in meter performance with frequency. Secondly, in those cases where the charge for energy is based on an arbitrary multi-part tariff designed to compensate the supply authority for the disadvantages due to reactive load on the system, errors may arise owing to the impossibility of obtaining meter torques proportional to products of currents and voltage of differing frequency, although the wattless energy in a distorted system contains such products.

A further problem may arise when metering the energy outputs of unsmoothed rectifiers, since the output consists of a combination of steady and pulsating energy. The latter component can lead to considerable error in the amount of energy recorded if it is metered on an instrument designed for measuring d.c. energy only.

(2) THE PROBLEMS INVOLVED

The theory of wave-form distortion in rectifier circuits is well known. Assuming, in the first place, sinusoidal voltage applied to the rectifier transformer, the wave-shape of the supply current is dependent on: (*a*) The number of rectifier phases. (*b*) The particular trans-

Table 1

Harmonic	Number of rectifier phases							
	2		3		6		12	
	S.*	U.S.†	S.	U.S.	S.	U.S.	S.	U.S.
Total	111	100	121	119	104·5	105	101	101
Fundamental	100	100	100	100	100	100	100	100
2nd	—		50	58·5	—	—	—	—
3rd	33·3		—	—	—	—	—	—
4th	—		25	14·6	—	—	—	—
5th	20		20	12·1	20	22·6	—	—
7th	14·3		14·3	8·6	14·3	11·3	—	—
8th	—		12·5	7·35	—	—	—	—
9th	11·1		—	—	—	—	—	—
10th	—		10	6	—	—	—	—
11th	9·1		9·1	5·5	9·1	9·1	9·1	9·1
13th	7·7		7·7	4·6	7·7	6·5	7·7	7·4
14th	—		7·1	4·3	—	—	—	—

* S. = smoothed output. † U.S. = unsmoothed output and pure resistance load.

former connections used. (c) The amount of reactance in the transformer and supply mains. (d) The amount of smoothing inductance in the d.c. output circuit. (e) The nature and the amount of the load.

Theoretical analysis is simple only when the particular

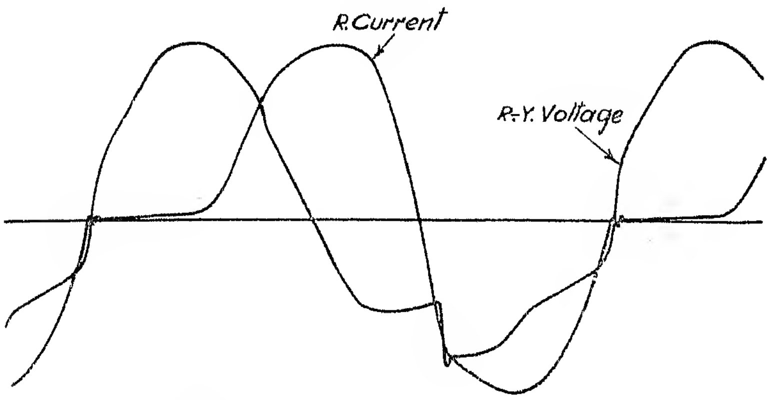


Fig. 1.—Three-phase connection.
(Line reactance)/(Transformer reactance) = 0·85.

cases are taken either of a pure resistance load, or of a completely smoothed load current, at the same time neglecting the transformer reactance and the modifications so introduced into the wave-shape owing to overlap of the rectifier phases. The relative amounts of current harmonics under these conditions are shown in Table 1 for various numbers of phases, up to the 14th harmonic.

In practice the departure from the theoretical values of distortion given in Table 1 is considerable, when all the factors (a) and (e) above are operative. To illustrate this, two typical practical cases have been taken, and the wave-forms obtained by oscillograms analysed for the first few harmonics. The results are given in Tables 2 and 3, and the oscillograms are shown in Figs. 1 and 2. It will be seen that the amount of current distortion is

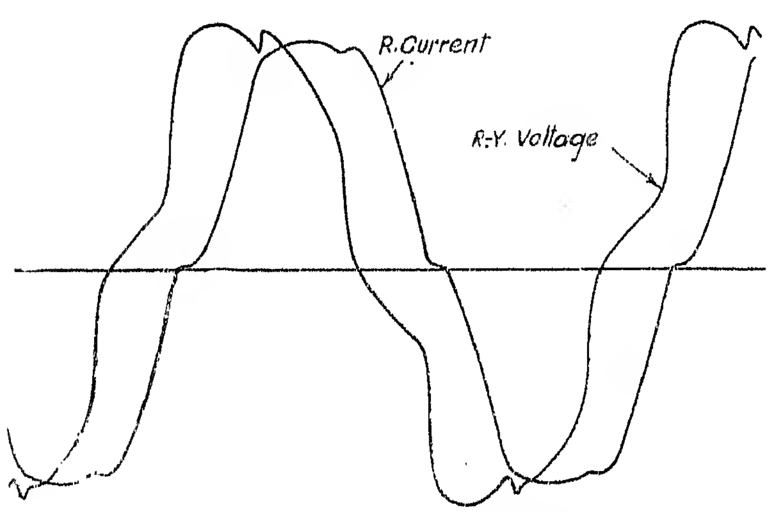


Fig. 2.—Six-phase connection.
(Line reactance)/(Transformer reactance) = 0·91.

somewhat less than that given by Table 1, especially in the case of the higher harmonics, but nevertheless the distortion met with in practice remains at considerable strength.

Under practical conditions there is very frequently, in addition to current distortion, a certain amount of voltage distortion at the rectifier transformer terminals in spite of an undistorted source of voltage supply. The cause of this is the voltage drop produced in line reactance between source and transformer by the already distorted currents. The amount of voltage distortion therefore depends on the ratio of line to transformer reactance. In the practical cases quoted in Tables 2 and 3, this ratio is stated and the harmonics so produced in the voltage wave are also given.

Table 2

CASE 1: 3-PHASE RECTIFIER. RATIO OF LINE TO TRANSFORMER REACTANCE, 0·85. REGULATION AT LOAD TESTED, 28 PER CENT. SMOOTHED D.C. LOAD CURRENT

Harmonic	Current I*		Voltage V†	Angular lag, I on V	Watts
	Actual	From Table 1			
	amps.	amps.	volts	degrees	
Total ..	112	121	103·2		100
Fundamental	100	100	100	60	120
2nd	50	50	22·8	225	− 19·1
4th	9·1	25	9·1	297	+ 0·9
5th	6·8	20	9·1	257	− 0·3

* Red-phase current. † Red-yellow phase voltage.

The total active power (P) supplied to a rectifier is the sum of the powers supplied at the various frequencies, i.e.

$$P = \Sigma E_n I_n \cos \phi_n$$

It is of interest to note that the sign of the harmonic power may be opposed to that of the fundamental component of the power. The author has shown elsewhere* more generally that, where a sinusoidal source

Table 3

CASE 2: 6-PHASE RECTIFIER. RATIO OF LINE TO TRANSFORMER REACTANCE, 0·9. REGULATION AT LOAD TESTED, 18 PER CENT. SMOOTHED D.C. LOAD CURRENT

Harmonic	Current I*		Voltage V†	Angular lag, I on V	Watts
	Actual	From Table 1			
	amps.	amps.	volts	degrees	
Total ..	104	104·5	101·2	—	100
Fundamental	100	100	100	50	101
5th ..	10	20	12·9	230	− 1·3
7th ..	4·3	14·3	9	308	+ 0·3
11th ..	0·5	9·1	2·4		0·0

* Red-phase current. † Red-yellow phase voltage.

supplies a non-linear impedance through a line impedance in which losses occur, the non-linear load behaves as a frequency-changer, and the harmonic losses in the line impedance are supplied from the load. It thus happens that the input to the load at fundamental frequency is higher than the loss absorbed, by the amount of the harmonic losses in the line impedance.

In Tables 2 and 3 the power inputs are shown for the various harmonics. It is seen that some are negative and

* C. DANNATT: *Journal of Scientific Instruments*, 1933, vol. 10, p. 285.

that the fundamental input is higher than the total input for this reason.

The amount of power supplied to rectifiers at frequencies other than the fundamental is dependent on the resistance of the line impedance, and where the latter is zero there is no such harmonic power, assuming always, of course, a sinusoidal voltage source. Generally, since the amount of current distortion decreases with number of rectifier phases, it follows that the higher the number of rectifier phases the lower is the component of input power at harmonic frequencies. This is again illustrated by the data of Tables 2 and 3. In the 3-phase rectifier 19 per cent of the power was at 2nd-harmonic frequency, whilst in the 6-phase rectifier the largest harmonic power was only 1·3 per cent at 5th-harmonic frequency. In the case of 12-phase rectifiers such powers are almost entirely negligible.

From what has been said it is apparent that an essential of an accurate meter for rectifier inputs is that the calibration should be independent of frequency, but that the stringency in such requirements decreases with the number of rectifier phases and also with improvement in voltage wave-form applied to the rectifier transformer.

Turning now to the question of power factor and reactive energy, the total volt-amperes or apparent power P supplied to a rectifier is

$$P_A = EI$$

and the active power (P) is given by

$$P = \Sigma E_n I_n \cos \phi_n$$

The reactive power as registered by a frequency-independent reactive meter is given by the expression

$$P_R = \Sigma E_n I_n \sin \phi_n$$

Actually, however, $(P^2 + P_R^2)$ does not equal P_A^2, on account of the products of volts and amps. of differing frequency which occur in $P_A = EI$. If we write

$$P_A^2 = P^2 + P_R^2 + P_D^2$$

P_D is solely composed of such products, and the total wattless power P_T can be expressed as

$$P_T^2 = P_R^2 + P_D^2$$

P_D is conveniently termed " distortion " power.

If then it is assumed that metering of a rectifier supply is carried out by the usual type of sine and cosine meters, neglecting any inherent errors in the meter, and that power factor, total kVAh, and wattless kVAh are deduced from the meters in the usual way, the following discrepancies will appear:—

	Actual values	As deduced from meters
Power factor	P/P_A	$P/\sqrt{(P^2 + P_R^2)}$
Wattless kVA ..	$\sqrt{(P_R^2 + P_D^2)}$	P_R
Total kVA	P_A	$\sqrt{(P^2 + P_R^2)}$

In order to instance the magnitude of error in these quantities, as metered in typical cases, they have been deduced for the cases given in Tables 2 and 3, on a 3-phase basis. The results so obtained are given in Table 4. There are, as would be expected, very considerable discrepancies in the values deduced from meter readings on the usual assumptions of sinusoidal current and voltage.

Table 4

	3-phase rectifier as in Fig. 1		6-phase rectifier as in Fig. 2	
	True values	Meter values	True values	Meter values
Power factor ..	0·71	0·89	0·89	0·94
Wattless kVA ..	71	37·2	45·6	33·1
Total kVA	100	79·5	100	94·8
Distortion power (P_D)	60·5		31·3	

Turning now to the wave-forms of the output voltage and current of rectifiers, Table 5 gives the theoretical values of the harmonics of the ripples in the no-load output voltage of rectifiers of varying numbers of phases, as percentages of the mean d.c. voltage.

In practice the wave-form of voltage depends on the load and is modified by the overlapping in the conduction of the rectifier anodes. The current wave-form also depends both on the amount of inductance in the d.c. load circuit and on the nature of the load, and this again affects the voltage wave-form. In Fig. 3, oscillograms

Table 5

Harmonics (r.m.s. values) in No-load Output Voltage as Percentage of Mean Voltage

Order of harmonic	No. of rectifier phases			
	2	3	6	12
2	47·13			
3		17·7		
4	9·44			
6	4·05	4·05	4·05	
8	2·25			
9		1·77		
10	1·43			
12	0·99	0·99	0·99	0·99
14	0·73			
15		0·63		
16	0·56			
18	0·44	0·44		

of wave-forms of the current in a few typical cases are given for cases where no smoothing existed in the output circuit, and these may be taken as extreme cases of current distortion for resistance loads. More pronounced ripples occur in special cases, such, for instance, as in

battery-charging circuits where the output voltage is largely balanced by the back e.m.f. of the battery. The wave-forms of Fig. 3 may, however, be regarded as examples of very marked ripples and are considerably worse than those usually met with commercially, such, for instance, as in rectifier-fed traction circuits.

The wave-form of Fig. 3(*c*) has been analysed, and gives

$$v = V_0 + 0\cdot 38V_0 \sin 3\omega t + 0\cdot 12V_0 \sin 6\omega t + 0\cdot 07V_0 \sin 9\omega t + \ldots$$

The energy associated with current and voltage of such wave-forms consists of a steady term and a series of pulsating terms, so that a meter used to measure the energy must maintain its accuracy at frequencies as high as the component frequencies of the composite wave-forms.

It is obvious that the proportion of pulsating energy to total energy decreases rapidly with the number of rectifier phases, so that difficulty in metering rectifier outputs is most likely to occur in rectifiers of low numbers of phases.

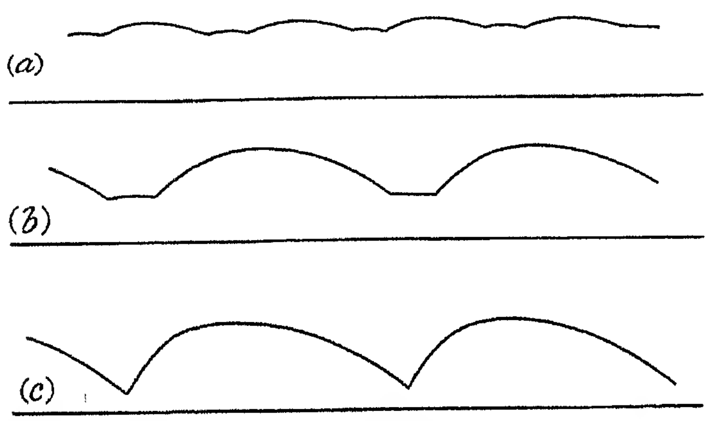


Fig. 3.—Output current and voltage wave-forms (unsmoothed, pure resistance load).
(*a*) 6-phase rectifier, 100 amps. load.
(*b*) 3-phase rectifier, 100 amps. load.
(*c*) 3-phase rectifier, 25 amps. load.

(3) ACTIVE-ENERGY METERING

It has already been explained that the fundamental requirement in a meter for precisely recording the active-energy input to a mercury-arc rectifier is that the meter performance should be independent of frequency over that range of frequency—including the fundamental and main harmonic frequencies—present in both voltage and current. In most commercial energy meters, although considerable effort has been made to ensure that the variation in calibration for small changes of frequency is almost negligible, no attempt has been made to produce a meter independent of large frequency-changes. Indeed, in many types of meter, correcting adjusters are used, such as light-load and quadrature adjustments, which are very definitely frequency-dependent. The theoretical conditions which must be met by any type of meter to be frequency-independent can usually be written down, but actual attainment is usually prevented by economic or practical considerations. The matter naturally becomes one of compromise, and in the case of rectifier metering it is a question whether or not the variation with frequency of any given meter is sufficiently small to prevent in practice the appearance of appreciable errors.

The induction meter has so many advantages from other points of view that when the question of metering rectifier supplies became prominent it seemed worth while to investigate carefully the errors likely to arise from its use, in spite of its known bad performance with frequency.

The nature of the effect of frequency on the performance of induction meters was well understood from the work of previous investigators,* but the magnitude of errors at harmonic frequencies was not known. As a preliminary, therefore, an ordinary type NE induction meter was tested for error at various power factors over a range of frequencies from 50 to 650 cycles. The meter was supplied from a sine-wave generator and the calibrations obtained by comparison with a standard reflecting wattmeter of proved accuracy up to 2 000 cycles. The meter was originally adjusted to read correctly at all power factors at 50 cycles, and the adjustments were not altered thereafter.

Fig. 4 gives the results obtained for constant volt-amperes at varying frequency and power factor. The changes in percentage error with varying load were not appreciable, excepting at very light loads. Whilst it is not strictly relevant to the purpose of the present paper, a slight digression in explanation of the observed results of Fig. 4 is worth while. The results can be expressed in the form

$$\text{Indicated watts} = K_f VI \cos(\theta + \alpha)$$

where K_f and α are both functions of frequency only. Actually α is the angular relation between the series and shunt fluxes when V and I are in quadrature, and at 50 cycles is adjusted to be zero. With increase of frequency α increases, mainly owing to an increase in iron loss and the effect of the anti-quadrature loop around the series-magnet pole. There is in addition a slight change in the angular position of the shunt flux with frequency.

The value of K_f is dependent on the ratio of resistance to reactance of the eddy-current paths in the disc and also on the reduction of current flux with increase of frequency due to the anti-quadrature loop. It is of interest to note that a meter having a purely resistive disc, no quadrature or anti-quadrature loops, and no iron or copper losses, would have a performance independent of frequency.

Knowing the frequency errors of the induction meter, it appeared reasonable to expect that its performance on a load of known distortion could be estimated. It seemed necessary, however, to check such estimated errors by actual tests when metering rectifier loads. For this purpose the rectifier circuit of Fig. 5 was used. The rectifier was of the 6-phase glass-bulb type, rated at 125 kW, 500 volts, d.c. A load of resistance grids was used, and tests were made with both 3-phase and 6-phase connections. The rectifier-transformer impedance referred to the primary, using all six phases, was 0·3 ohm per phase; and, with three phases, 0·32 ohm. Line reactors were used in order to give voltage distortion at the transformer primary terminals. The value of the reactance per phase could be varied from 0 to 0·8

* H. A. Ratcliff and A. E. Moore: *Journal I.E.E.*, 1911, vol. 47, p. 3; also A. E. Moore and W. T. Slater: *ibid.*, 1930, vol. 68, p. 1023.

ohm. Current and voltage transformers were used to supply the energy meter and the standard wattmeter, but, since the same instrument transformers were used for both instruments, transformer errors, if transformer so that the wave-form of the current was not varied.

The rectifier regulation was measured for each condition of test, i.e. for each value of line reactance. In all

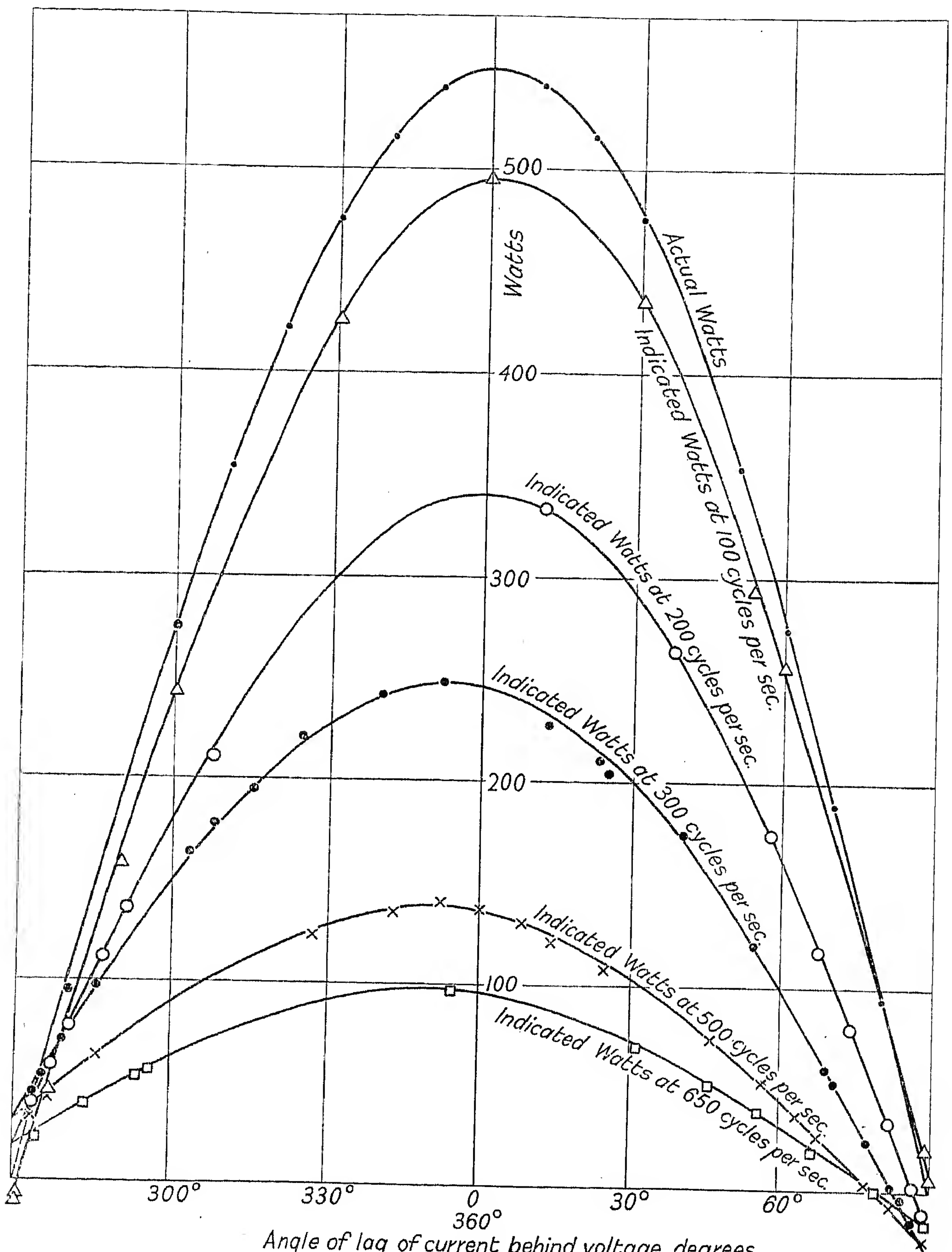


Fig. 4.—Results obtained with meter supplied at 110 volts, 5 amps.

present, would not affect the comparisons. The two-wattmeter connection was adopted in all cases and the meter was checked in each of the two positions. Most of the tests were carried out at full-load volt-amperes for the meter, but when tests were made at other loads the variation was obtained by change of ratio of the current cases the voltage at the supply end of the lines was maintained constant. The regulation is dependent on the degree of overlap of the rectifier anodes and is therefore indirectly an indication of the amount of distortion of the current wave.

The meter errors with rectifier supply were always

deduced from the meter calibration with sinusoidal conditions at a power factor corresponding to the phase angle between the fundamental current and voltage in the rectifier tests; so that it should be understood that the errors referred to are due solely to the distorted supply conditions and are in addition to any meter error present under sinusoidal conditions.

The results obtained are shown in Fig. 6. Fig. 6(*a*) refers to a 3-phase rectifier connection, and Fig. 6(*b*) to a 6-phase connection. Results are given for both positions of the two-wattmeter connection, and also for the combined results, such as would be recorded by a 2-element polyphase meter. All results are plotted to a base of ratio of line to transformer reactance. Consequently at zero on the abscissae the errors correspond to the condition of distorted current with sinusoidal voltage. As it was impossible to remove the last trace of voltage distortion under this condition, however, the tests were repeated for this condition using a voltage on the meter obtained from a different machine from that supplying the rectifiers, but running synchronously with it. This machine was of pure sine wave-form. These tests con-

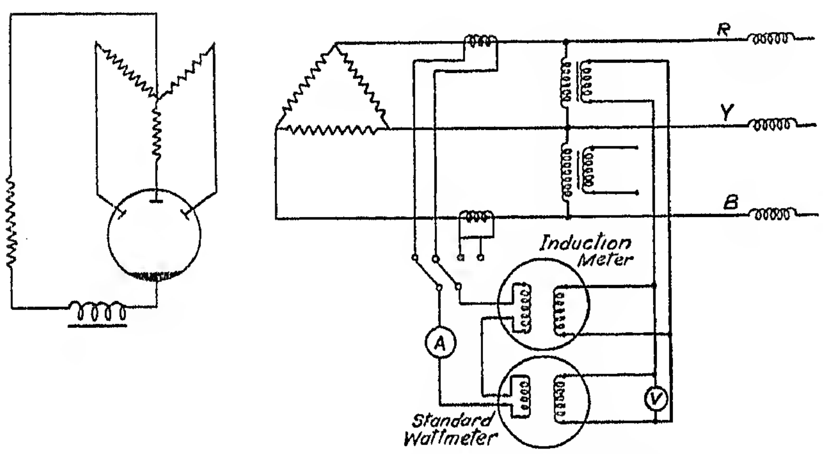


Fig. 5.—Test circuit for checking meter errors.

firmed those of Fig. 6 and demonstrated that a small error existed in the meter under conditions of distorted current and sinusoidal voltage. It is significant that all errors are positive, which confirms the point previously made that the losses at harmonic frequency in line reactances are supplied from the rectifier.

With both 3- and 6-phase rectifiers the error increases with increase of line reactance in the lagging-current element, whilst the reverse is the case in the leading-current element. This has the peculiar result that the combined error is practically independent of the amount of voltage distortion. The error reaches appreciable magnitude in the lagging-current phase of the two-wattmeter connection, but as this element is carrying a small proportion of the total watts the error is not important.

The results are confirmed, at least qualitatively, by the meter error calculated from the analysis of oscillograms and the frequency characteristics of Fig. 4. Typical oscillograms for the 3- and 6-phase rectifiers (as shown in Figs. 1 and 2) have already been referred to. Table 6 gives a comparison of the calculated and actual errors (see Fig. 6) for these two cases, using the analysis of the oscillograms and the data of Fig. 4.

The observed errors are, however, higher than the expected errors in the case of low line reactance, where the harmonic power is nearly zero. In tests conducted to discover the reason for this it was found that the correctors (anti-quadrature and light-load loops) affected the accuracy of the meter when metering distorted current, and increases in error of 1 per cent were readily produced by their maladjustment. It was found, however, that with all adjusters removed there was still a slight difference in calibration when using a distorted rectifier

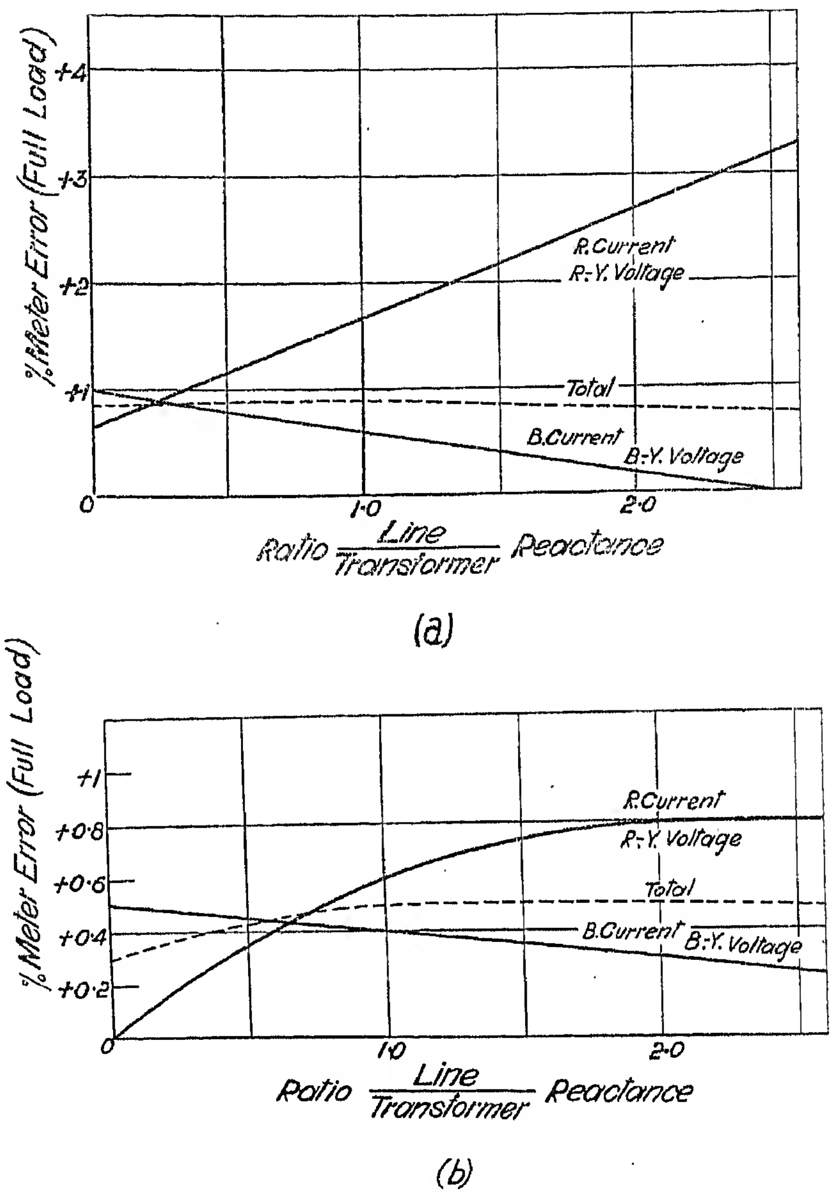


Fig. 6

(*a*) 3-phase connection.
(*b*) 6-phase connection.

current in place of a sinusoidal current. It was therefore necessary to conclude that this remaining error was due to non-linear effects in the iron circuits. This was partly confirmed by tests at overloads, when it was found that the error began to increase considerably. Fig. 7 gives a load/error curve for one condition, and is typical.

The conclusion from the tests is that the error of a modern well-designed induction meter when metering rectifier supplies is not likely to exceed + 1 per cent with a 3-phase rectifier connection, and + 0·5 per cent with a 6-phase rectifier connection, provided the meter is adjusted to register correctly with sinusoidal current and voltage. This applies not only to the case of sinusoidal voltage and distorted current, but also to any case of distorted voltage and current likely to arise in practice in rectifier circuits.

Table 6

ESTIMATED AND ACTUAL ERRORS OF INDUCTION-TYPE WATT-HOUR METER ON RECTIFIER INPUT

Connection	Harmonic	True watts	Estimated watts	Percentage error	
				Estimated	Actual
3-phase, as Fig. 1, lagging-current element	Fund. 2nd 4th 5th	+ 250·5 − 40·3 + 1·9 − 0·7	+ 250·5 − 37 + 1·3 − 0·2		
	Total	+ 211·4	+ 214·6	+ 1·51	+ 1·5
3-phase, as Fig. 1, leading-current element	Fund. 2nd 4th 5th	+ 501 − 14·7 + 2·3 + 2·3	+ 501 − 12·5 + 1·3 + 1·3		
	Total	+ 490·9	+ 491·1	+ 0·04	+ 0·65
6-phase, as Fig. 2, lagging-current element	Fund. 5th 7th 11th	+ 356 − 4·6 + 1·3	+ 356 − 2·2 + 0·6		
	Total	+ 352·7	+ 354·4	+ 0·48	+ 0·55

In view of the satisfactory performance of induction meters when measuring the active energy supplied to rectifier circuits, it seemed reasonable to expect that other types of meters which are capable of use on either direct current or alternating current and therefore much less frequency-dependent in calibration than the induction meter, would be even more accurate than the induction meter. The Thomson motor meter and the pendulum clock meter both fall into this category. The author has only had the opportunity of testing a meter of the Thomson type in rectifier circuits.

The meter used had current coils with a full-load rating of 30 amps. and was designed for use with an external shunt, temperature correction being obtained by using a shunt of negligible temperature coefficient. For convenience in the tests the meter was used without a shunt and all readings corrected for temperature by the measured temperature coefficient of the meter.

The meter had the following constants: resistance of voltage-coil circuit (r), 5 620 ohms; inductance of voltage coil (L), 0·30 henry; mutual inductance of starting coil (M), 0·00115 henry; resistance of field coils at 20° C., 0·0195 ohm; inductance of field coils, 59·5 microhenrys.

The torque on the meter can very readily be shown to be

$$\mathrm{T} = \frac{k}{r^2 + \omega^2 L^2}(VIr\cos\phi + \omega LVI\sin\phi - \omega^2 MLI^2) \quad . \quad (1)$$

where, in addition to the symbols already given, V and I are the voltage and current respectively, $\omega = 2\pi f$, and ϕ is the angle between the vectors V and I.

The meter was calibrated at 50 cycles and also at 500 cycles. In Fig. 8 are given calculated calibration curves at 500 cycles based on the 50-cycle calibration and formula (1). Test points are also given on the curves, and show almost exact agreement. It will be noted that the error of the meter at 500 cycles and full load was only 13 per cent, whilst that of the induction meter at the same frequency was 75 per cent. From this it follows

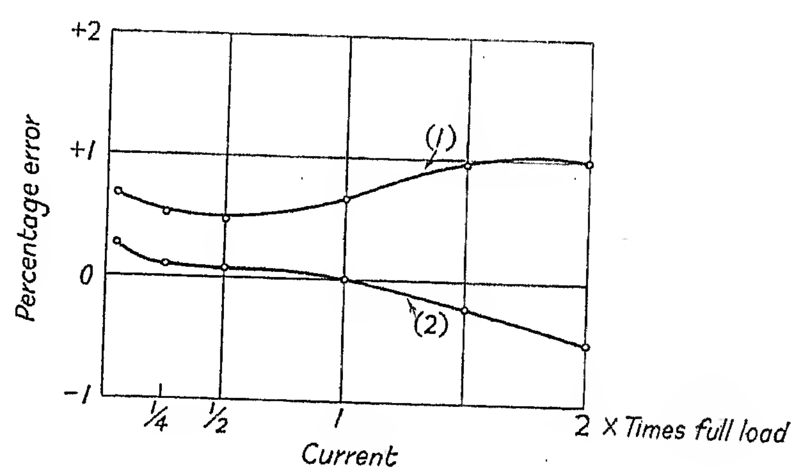


Fig. 7.—Load/error curves.

(1) R. current, R.-Y. voltage, 3-phase rectifier.
(2) Sinusoidal current and voltage, 50 cycles per sec., unity power factor.

that the error when metering rectifier inputs with large percentages of harmonic power would be very much smaller than the error obtained with the induction meter, which was itself correct within 1 per cent.

The meter was, however, checked on the 3-phase rectifier circuit of Fig. 5, with sinusoidal voltage and 2nd, 4th, and 5th current harmonics of 50, 9·1, and 6·8 per

cent respectively of the fundamental. The measured error of the meter under this condition was $-0{\cdot}2$ per cent, whilst that calculated from formula (1) showed an expected error of $-0{\cdot}1$ per cent.

It may therefore be concluded that the Thomson meter is sufficiently independent of frequency to make it an accurate instrument for rectifier power-input measurements, when no shunt is used for feeding the field coils. If a non-inductive shunt is used, then a considerably enhanced frequency-error is introduced owing to the differing time-constants of the shunt and the field coils. In the meter tested, the ratio of the 50-cycle reactance of the field coils to their resistance was 0·96, implying an angle of 44° between the voltage across and the current in the coils at 50 cycles. This angle would rapidly approach 90° at the orders of harmonics present in rectifier circuits, and the impedance of the coils would continuously increase with frequency. It would therefore be necessary to use a shunt with the same time-constant as the field coils to overcome this difficulty. Whilst this could be reasonably well achieved, it would be done with the sacrifice of part of the temperature compensation of the meter as ordinarily obtained. There are, however, no serious objections to the introduction of temperature compensation into the voltage-coil circuit, so that this difficulty could also be overcome. Alternatively, with complete temperature compensation of the latter type, the meter could be used without a shunt.

With these modifications, therefore, it would appear that the Thomson meter could be made as accurate for rectifier circuits as it is for normal a.c. power metering. The recognized disadvantages of this type of meter, such as the difficulty of commutator maintenance and maintenance of light-load accuracy, would still remain, and would have to receive due weight when this type was under consideration for rectifier metering.

(4) WATTLESS-kVA METERING

There are several well-known methods* which utilize cosine meters connected in a 3-phase circuit in such a manner as to convert them into sine meters. Such methods include the single-element method, the crossed-phase method, and the composite-voltage method. The advantages of one or other of the methods lies in the effect of unbalanced conditions on the accuracy of the readings. In addition, there are other methods which employ a change of connection combined with an alteration to element design to change the phase of fluxes in the meter relative to applied voltage or current.† In the latter case this relation is usually frequency-dependent.

It is apparent that any of the former methods will record the integrated product of voltage with out-of-phase current, i.e. P_R, with similar accuracy to that with which similar-type cosine meters record active energy in rectifier circuits. The same applies to methods of the second type, with the additional proviso that reactive energy of harmonic frequency, if present, will be recorded with a further error dependent on the method adopted to modify the phase of the fluxes in the meter, and the influence of frequency on such phase modification.

Further, it has already been shown that when harmonics are present in current and/or voltage, integrating meters do not register the total wattless power P_T but only that part defined as P_R.

It is necessary, therefore, when considering reactive meters for rectifier circuits, to distinguish between the inherent meter errors brought about by the change of performance with frequency and those due to the impossibility of measuring the required quantity P_T, but only that part of P_T represented by P_R.

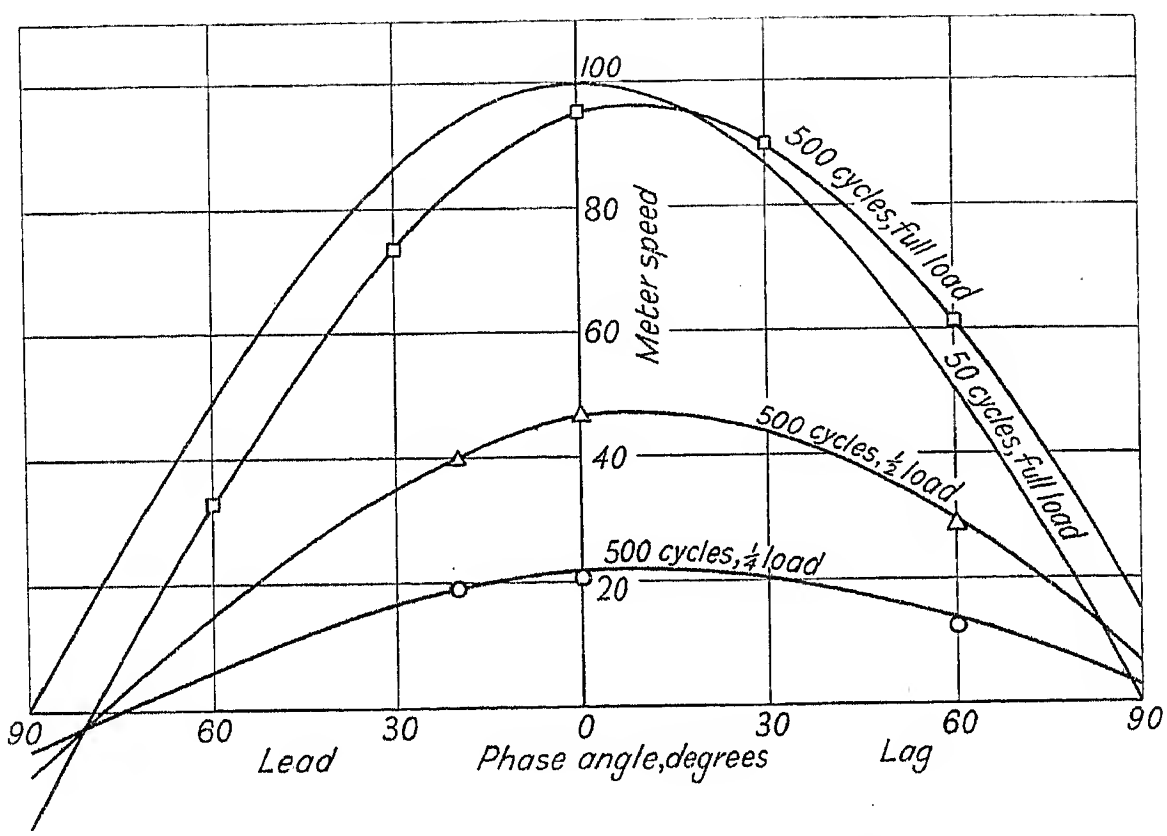


Fig. 8.—Effect of frequency and load on Thomson meter.

* Discussion on Mr. Spilsbury's paper: *Journal I.E.E.*, 1933, vol. 73, p. 240.
† G. A. Cheetham: *Journal I.E.E.*, 1933, vol. 73, p. 233.

It appears, therefore, that the only method of approach open in the application of existing types of meter to the measurement of wattless kVA and the associated quantities total kVA and power factor, is to consider the possibility of using them in conjunction with calculated or empirical correcting relationships between the quantities measured and those required, providing these can be determined. Following up this possibility, tests were made on a 6-phase rectifier with smoothed d.c. output and sinusoidal supply voltage. The supply was metered on the primary side of the delta/star transformer by means of a 2-element 3-phase induction-type kWh meter and a 2-element induction-type reactive-kVAh meter. This latter meter was of the type described by Cheetham, in which the phase-difference between the current and voltage fluxes is moved 30° by means of a short-circuited winding on the current magnet and resistance

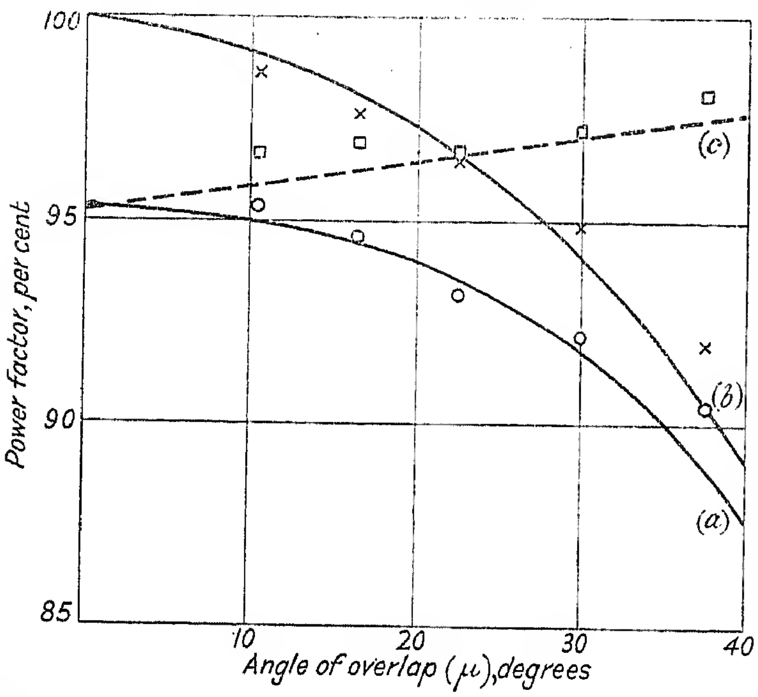


Fig. 9.—Estimation of true power factor from sine- and cosine-meter readings. (6-phase delta/star connection.)

(a) True power factor (check points O).
(b) Meter power factor (check points +).
(c) Theoretical ratio a/b (check points □).

in the voltage-coil circuit, and a further 60° displacement is obtained by choice of voltage. Thus on an undistorted and balanced 3-phase system the meter reads reactive kVAh correctly. The voltages, currents, and watts of the circuit were also measured by means of frequency-independent meters, so that the true power factor could be deduced.

Fig. 9 shows the values obtained with varying load for the true power factor and also the power factor deduced from the sine and cosine meters. As expected, the discrepancies are very large.

For the particular conditions of the test it was possible, by means of the theory outlined in Appendix 1, to calculate the expected error in power-factor measurement, on the assumption that the meters had frequency-independent characteristics. These corrections are shown in Fig. 10, and the effect of applying them to the observed readings is also indicated in Fig. 9. It will be seen that the readings corrected in this manner are very close to the true values.

It appears, therefore, that there is a possibility of using the data of Fig. 10 to correct the reactive-kVA readings, or power-factor readings, of sine meters when operating conditions of the rectifiers are favourable. The difficulty arises that the factor to be used varies with load. The variation is fortunately not large over the normal range of load, and a mean factor could probably be used to give a mean result within 1 per cent or so of the true value. The correction curves of Fig. 10 are plotted against angle of overlap. As explained in the Appendices this can, for any given system of connections, be translated into d.c. regulation of the rectifier, and therefore into load-current magnitude.

The example cited has been given for the case of sinusoidal voltage. When the supply voltage is distorted, owing to line reactance, the correction factors of Fig. 10 do not apply and the discrepancies in deduced power factor become dependent on factors which do not lend themselves to easy calculation. The same objection

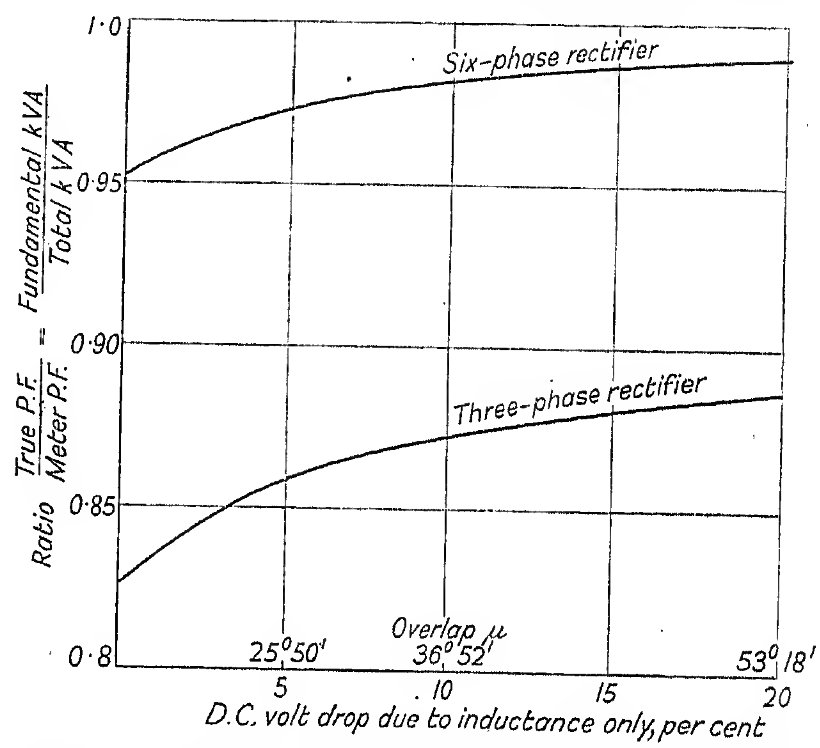


Fig. 10.—Correction factors for kVA and power-factor readings, using sine and cosine induction meters.

arises in the case of metering the wattless power in a mixed load consisting only partly of rectifiers, and also to a lesser extent in all cases due to the presence of transformer magnetizing current in the metered load. In most practical cases the magnetizing kVA of the transformer is only a few per cent of the full-load kVA, and the error due to its presence is only important at light loads. This is borne out by the test data of Fig. 9, in which the magnetizing kVA was about 5 per cent of the full-load kVA. Cases do arise, however, in which the transformer magnetizing kVA increases with rectifier load as the result of d.c. magnetization of the transformer core, brought about by the secondary load. The most common rectifier connection which causes such an effect is that in which a delta/star transformer supplies a 3-phase rectifier. With this connection, if I is the d.c. load current and N_2 are the secondary turns per phase, there are $(IN_2/3)$ d.c. ampere-turns on each leg, acting in the same direction. A d.c. flux is therefore established in the core, completing its magnetic circuit from yoke to yoke

by way of the air and tank sides. This d.c. flux increases as the load increases, and a magnetizing current containing large even harmonics is taken from the supply. This current may become very large, of the same order, in fact, as the load component of current, and the input power factor is greatly reduced. In a particular case which came to the author's notice, the primary current was increased by 33 per cent at full load, owing to this cause. It is of interest to note that a zigzag connection of the secondary winding removes this type of effect.

It would appear from the foregoing that at the moment there is no entirely satisfactory manner of metering wattless power in rectifier circuits, and the same remark therefore applies to power-factor and total-kVA metering in those methods where a reactive-power meter is necessary. In 6- and 12-phase rectifier circuits where no other appreciable load is included in the circuit, readings of an accuracy sufficient for most commercial requirements can be obtained by using theoretical relationships to correct the readings of sine meters.

(5) DIRECT-CURRENT METERING

The meters in most general use for metering d.c. power are either of the mercury-motor type or of the Thomson dynamometer type.

It has already been shown that the Thomson-type meter when used without a shunt has very small frequency error. The estimated error of the Thomson meter already referred to, when metering the current of Fig. 3(*c*) in a pure resistance load, was $-0\cdot 09$ per cent. On an actual test no difference could be detected between the calibration of the meter on this wave-form from that on pure direct current. This test was made without a shunt, and the results were corrected for temperature. As previously pointed out in the case of this meter used for input measurements, accuracy of reading when it is used with a shunt will depend on the time-constants of the shunt and field coils being the same. The estimated error of the meter used with a 10:1 non-inductive shunt on the wave-form of Fig. 3(*c*) is -11 per cent, so that it is again clear that the Thomson meter can only be considered satisfactory for distorted-output measurements when modified in the manner already suggested for input measurements.

Mercury meters consist essentially of a current circuit through the disc (usually shunted across a low external resistance for meters of high current values), together with a voltage element which produces a flux proportional to voltage. Consequently, as with the Thomson meter used with a shunt, a frequency error may arise unless the time-constants of shunt and disc circuit are identical. Also, if the inductance of the voltage-coil circuit is comparable with its resistance, the flux due to the alternating component of voltage is no longer in phase with the voltage, so that the pulsating energy will be inaccurately registered.

Tests were made on a standard 200-volt 40-amp. meter with external non-inductive shunt, on a 3-phase rectifier output with the wave-forms of Fig. 3(*b*) and Fig. 3(*c*), and also on a 6-phase rectifier output with the wave-form of Fig. 3(*a*). The recorded errors of the meter under these various conditions are given in Table 7.

The phase defect of the disc circuit was measured and found to be only $0\cdot 024$ at 50 cycles, so that the error due to frequency error in the disc and shunt circuit was in any case small. On the other hand, the estimated errors due to the inductance of the voltage-coil circuit were by no means negligible. The constants of this circuit, as obtained by measurement, were: d.c. resistance, 10 000 ohms; 50-cycle resistance, 11 800 ohms; inductance, $44\cdot 6$ henrys.

In Appendix 2 an expression is derived for the error due to this cause on a known wave-shape, and for the case of Fig. 3(*c*) the calculated error was found to be $-6\cdot 5$ per cent. The measured error was $-6\cdot 1$ per cent. It is therefore obvious that the main cause of error in the meter tested is the inductance of the voltage coil.

The reduction of error at the higher loads, as shown in Table 7, is due to the decrease in the ripple, as the load increases, brought about by increased overlap of the rectifier phases due to transformer inductance.

Table 7

Connection	Load current	Load volts	Meter error	Ripple
			per cent	per cent
3-phase, unsmoothed	$\frac{1}{4}\times$ f.l.	200	$-6\cdot 1$	92
	$\frac{1}{2}\times$ f.l.		$-5\cdot 8$	
	$\frac{3}{4}\times$ f.l.		$-4\cdot 0$	
	$1\times$ f.l.		$-2\cdot 5$	66
6-phase, unsmoothed	$1\times$ f.l.	200	$-0\cdot 5$	16

The test on the 6-phase rectifier, even though unsmoothed, is sufficient to show the rapid increase in accuracy in the meter readings as the ripple is reduced. In fact it is evident that appreciable inaccuracy is only likely to arise with this particular meter in its standard form in the case of 2- or 3-phase rectifiers, and then only when the smoothing is small. Moreover, the cause of error is one which can be very considerably reduced by change in design, since by the use of greater volt-amperes in the voltage-coil circuit the power factor can be proportionately increased, and the error reduced.

It will be noted that with this type of meter the normal method of temperature compensation can be used, since the inductance of the current circuit is low. The remaining objection to this class of meter is one which exists independently of the distortion of the load, and is due to hysteresis effects in the iron of the voltage circuit causing change of calibration with voltage. It is probable that this is the largest source of error which arises with the mercury meter, especially on traction loads, where the variation in circuit voltage is very large, and it seems likely that if this effect were eliminated the meter could be made satisfactory for most rectifier outputs likely to occur in practice.

(6) CONCLUSIONS

The investigations described in the paper are to be taken as a review of the difficulties and sources of error in metering problems in rectifier circuits, and it is hoped that they will serve as a guide in specifying metering equipment for such purposes.

In the case of a.c. metering, it has been shown that

induction-type watt-hour meters can be entirely satisfactory. In spite of large errors in this class of meter at harmonic frequencies, the amount of power at such frequencies is not large excepting in the case of 2- or 3-anode rectifiers, so that the overall error is small. Meters of the Thomson type, with modifications necessitated by the shunt-feed system to the field coils, can be made satisfactory, and in the case of high-number-of-anode rectifiers would be sufficiently accurate in spite of shunt errors, again for the reason that the harmonic power is small. On the other hand, other disadvantages of the Thomson-type meter would appear to give the induction type a considerable advantage.

The conclusions regarding watt-hour meters apply equally to inherent meter errors in reactive-power meters, but there is here the further difficulty of metering the "distortion power" component. It has been shown that for certain favourable conditions in rectifier circuits theoretical relationships can be used to correct meter readings for this component. As far as the author is aware, however, there is no entirely satisfactory method of measuring wattless power, power factor, or total kVA, in rectifier circuits.

Table 8

p	K_1	K_2
3	0·826	4·5
6	0·957	3
12	0·99	1·61

Finally, with regard to output metering, standard mercury meters may be subject to error due to the inductance of the voltage coil. This could be obviated by re-design, to reduce the phase error of this circuit. Thomson meters are satisfactory providing the frequency error in the shunt circuit is eliminated.

Apart from the above considerations, the factors which govern the choice of meter are identically those met with in choosing meters for undistorted circuits.

The author wishes to thank Mr. G. A. Cheetham for his support of work leading to this paper; and his colleagues, especially Mr. F. H. Belsey, for their able assistance in collecting the data. He is also indebted to Dr. A. P. M. Fleming, C.B.E., and to the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the paper.

APPENDIX 1

The power factor of a p-phase rectifier supplying smoothed direct current is given by*

$$\frac{K_1 \cdot \frac{1}{2}[\cos\alpha + \cos(\mu+\alpha)]}{\sqrt{[1 - K_2\psi(\mu\alpha)]}} \quad . \quad . \quad . \quad (1)$$

where

K_1 and K_2 are constants characteristic of the type of connection, and

$\psi(\mu\alpha)$ is a function of the angle of overlap (μ) and the angle of grid retard (α). The latter is, of course, equal to zero in uncontrolled rectifiers.

The values of K_1 and K_2 are given in Table 8 for various values of p.

The function $\psi(\mu\alpha)$, which takes account of the overlap, is given by

$$\frac{1}{2\pi}\left\{\frac{\sin\mu[2+\cos(\mu+2\alpha)]-\mu[1+2\cos\alpha\cos(\mu+\alpha)]}{[\cos\alpha - \cos(\mu+\alpha)]^2}\right\}$$

The angle of overlap (μ) is determined by the relation

$$\cos(\mu+\alpha) = \cos\alpha - \frac{IX}{E\sin(\pi/p)}$$

where

I is the direct current,

X is the reactance per phase referred to the transformer secondary, and

E is the peak value of the phase voltage.

μ is also related to E_l (the d.c. voltage under load) and E_0 (the open-circuit voltage, with $\alpha = 0$) by the equation

$$\frac{E_l}{E_0} = \tfrac{1}{2}[\cos\alpha + \cos(\mu+\alpha)]$$

The apparent power factor for smoothed-output rectifiers, obtained from the readings of sine and cosine meters, is equal to the cosine of the angle ϕ_1 between voltage and fundamental current. It is usually referred to as the displacement factor. An expression for it is derived below.

The form of anode current in each anode of a smoothed rectifier is shown in Fig. 11. Using the notation already given, and putting $\theta = 0$ at the commencement of the corresponding phase-voltage zero, the values of current are as follows:—

From $\theta = 0$ to $\left(\frac{\pi}{2}-\frac{\pi}{p}\right)$, $\quad i = 0;$

$$\theta = \left(\frac{\pi}{2}-\frac{\pi}{p}\right) \text{ to } \left(\frac{\pi}{2}-\frac{\pi}{p}+\mu\right), \quad i = \frac{I}{1-\cos\mu}\left[1 - \cos\left(\theta - \frac{\pi}{2}+\frac{\pi}{p}\right)\right];$$

$$\theta = \left(\frac{\pi}{2}-\frac{\pi}{p}+\mu\right) \text{ to } \left(\frac{\pi}{2}+\frac{\pi}{p}\right), \quad i = I;$$

$$\theta = \left(\frac{\pi}{2}+\frac{\pi}{p}\right) \text{ to } \left(\frac{\pi}{2}+\frac{\pi}{p}+\mu\right), \quad i = \frac{I}{1-\cos\mu}\left[\cos\left(\theta-\frac{\pi}{2}-\frac{\pi}{p}\right) - \cos\mu\right];$$

$$\theta = \left(\frac{\pi}{2}+\frac{\pi}{p}+\mu\right) \text{ to } 2\pi, \quad i = 0.$$

* C. C. Herskind: *Transactions of the American I.E.E.*, 1934, vol. 53, p. 926.

Expressing i in the form

$$i = a_1 \cos \theta + a_2 \cos 2\theta + \ldots + b_1 \sin \theta + b_2 \sin 2\theta + \ldots$$

where
$$a_1 = \frac{1}{\pi}\int_0^{2\pi} i \cos \theta d\theta$$

$$b_1 = \frac{1}{\pi}\int_0^{2\pi} i \sin \theta d\theta$$

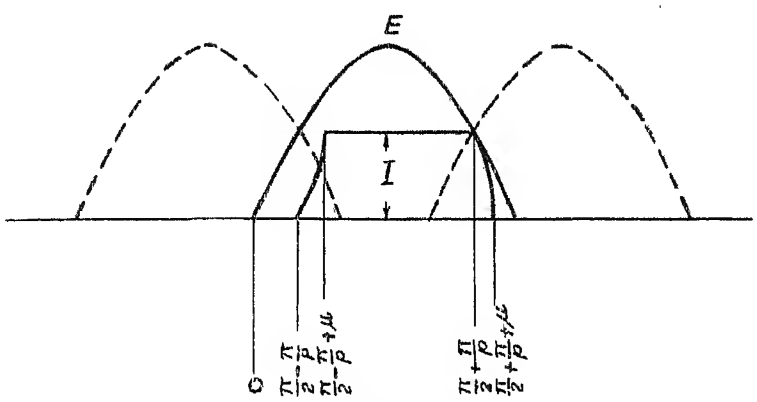


Fig. 11

and integrating by steps between the limits given, one obtains

$$i = \frac{I}{(1 - \cos \mu)\pi} \sin \frac{\pi}{p}[(\mu - \sin \mu \cos \mu) \cos \theta + \sin^2 \mu \sin \theta + \ldots]$$

from which the displacement factor is obtained in the form

$$\cos \phi_1 = \frac{1}{\left[1 + \left(\frac{\mu - \sin \mu \cos \mu}{\sin^2 \mu}\right)^2\right]^{\frac{1}{2}}}$$

In grid-controlled rectifiers with smoothed output in which the anode ignition is retarded by an angle α, the angle ϕ_1 is obviously increased by the angle α.

The relations of Fig. 10 have been derived directly from formulae (1) and (2) above.

APPENDIX 2

The Error of a Mercury Meter due to Voltage-circuit Inductance when Metering Unsmoothed Outputs

The voltage and current forms in the case of resistance load are respectively

$$v = V_0 + \Sigma V_n \sin n\omega t$$
$$i = I_0 + \Sigma I_n \sin n\omega t$$

where $n\omega$ has particular values dependent on the connections (see Table 5).

The output power P is therefore expressed as

$$P = V_0 I_0 + \Sigma \tfrac{1}{2} V_n I_n$$

Calling the d.c. and a.c. resistances of the voltage circuit R_0 and R respectively, and L the inductance, the power recorded by the meter is

$$P_m = V_0 I_0 + \Sigma \frac{V_n I_n}{2} \cdot \frac{R_0 R}{(R^2 + \omega^2 n^2 L^2)}$$

Hence the percentage error in the recorded watts is

$$\frac{P - P_m}{P} \cdot 100 = \frac{\Sigma V_n I_n \left(1 - \frac{R_0 R}{R^2 + \omega^2 n^2 L^2}\right) \cdot 100}{2 V_0 I_0 + \Sigma V_n I_n}$$

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 5TH MARCH, 1937

Mr. O. Howarth: Very little information about the performance of meters on distorted loads has been made public, despite the fact that our meters, more frequently, perhaps, than we realize, have to register these distorted loads. Even the ordinary single-phase meter may have to register loads as bad as or worse than some of those shown in Fig. 1.

Fig. 7 is interesting as showing that the double-load feature is different when the meter is supplying a distorted wave. These double-load features are inclined to be fickle, and different meters even of the same type may give rather different relations between the two curves.

From Fig. 6 it seems apparent that if it were possible to ban the use of 3-phase rectifiers in the interests of sound metering it would be desirable to do so. Unfortunately we cannot do that, but the results shown in Fig. 6(*a*) are encouraging, seeing that they are correct within 1 per cent; in Fig. 6(*b*) also the error due to the distortion is very small indeed.

The author has made some attempt to measure reactive kVA. Reactive kVA and power factor have very little influence upon the costs of supply undertakings, but they have a great deal of influence on some people's minds, owing to the publicity given to them by those who sell power-factor correction apparatus. I have investigated several supplies with a view to seeing what rebates could be given if consumers would improve their power factors, and the reduction in losses due to such improvements has turned out to be very small in every case.

Mr. T. S. Pick: When new rectifiers are first put on load their efficiency as recorded by commercial meters may be anything from 80 to 110 per cent on alternate days; it is not until the plant has been on load for some considerable time that a definite efficiency value can be obtained. To investigate this effect, very careful checks have been made on rectifiers, specially calibrated a.c. and d.c. meters being used. The tests were found to be useless, however, owing to the hysteresis characteristic of the d.c. meter. A clock-type meter was then used on the d.c. side, quarter-hour readings being taken, with no better results. It was not until periods over 40 minutes were taken, which was apparently the natural period of the meter, that anything like reasonable efficiencies were obtained, but even then the results were very extraordinary. Every day, when starting up on load, there was invariably an efficiency of over 100 per cent for the

first 40 minutes, and over the whole 24 hours an efficiency 2 to 4 per cent greater than the maker's guarantee was always obtained. This paper would lead one to believe that ordinary commercial meters are incapable of such results, and from the author's curves it would appear that the a.c. meters were fast and the d.c. meters slow—the exact reverse, apparently, of what has been found.

A new d.c. meter is to be tried out, in the hope that better results will be obtained, but from the correspondence which has passed in the buying of these meters it seems that the external fields play a tremendous part in the readings. A commercial instrument is needed which will be reliable, particularly on traction systems where the external fields may be of any magnitude.

Regenerative braking is becoming quite a popular subject, and I should therefore like to know how, if a mercury-arc rectifier is run inverted, the regenerative power is measured.

Mr. E. Fawssett: It is very comforting to notice that with the type of rectifier shown in Fig. 3 the wave-form improves with the load. Unfortunately, that characteristic is not universal. The grid-controlled rectifier exhibits different characteristics altogether, and such a rectifier on a traction load gives a voltage-output wave which is worse on full than on light load.

It seems to me that there is nothing very much to worry about regarding the input kW metering, which is reasonably accurate, but in our case particularly that problem does not usually arise, because nearly always the metering is on the d.c. side, for a reason which I will mention later. I think, however, that if engineers set out to frame a tariff with metering on the a.c. side they would have to be very careful about the power-factor clause. It would be much better to consider the type of rectifier which was going to be put in, and frame a unit tariff taking account of the power factor to be expected; otherwise we should have to have something in the agreement which does not talk about power factor but refers to sine and cosine measurements.

The author dismisses the d.c. side rather summarily; in our case all the rectifier supplies are measured on direct current. Unfortunately, for various reasons, some of which have already been mentioned and one of which I shall mention in a moment, most types of d.c. meter seem to increase the consumer's bill, which is very bad for the supply undertaking if, purely to suit its own purpose, it wants to change the consumer over to a new system through a rectifier.

In the case of a grid-controlled rectifier equipment of moderate size with which I am acquainted, supplying a relatively small number of trolley-buses in an isolated area, the conditions of supply were such that the load dropped off completely every few minutes. Two different types of mercury motor meters persistently read higher on this type of supply than in the test room, and for a long time we could not discover the reason. In the end we installed an oscillograph and found that in one cycle the voltage rose from 520 to 850 volts, a 60 per cent rise. What happened was that the flux in the iron of the meter was stroked up for a cycle or two, and it took about 4 hours to come back to normal, the average reading being about 5 per cent up.

It is of interest to know how the mercury motor meter deals with the a.c. component on the d.c. side. Owing to the time-constant of the shunt coil, the meter runs fastest at nearly zero lagging power factor, so that, when picking up the a.c. part of the energy output, the accuracy of the meter is dependent on the phase relationship between the voltage and the current. Actually, in one type of meter at any rate, the alternating part of the energy is correctly recorded at about 45° current lagging.

Mr. A. E. Quenzer: My interest in this paper is concerned with the output of mercury-arc rectifiers supplying traction loads. A considerable number of substations have been erected in the London area during the last 18 months to deal with the new trolley-bus system, the capacity of the substations being between 500 and 1 000 kW. With one exception, all are 12-phase rectifiers. Oscillograms were taken of the wave-form under varying conditions and also of the d.c. ripple; this ripple at full load of the rectifier was not very pronounced as compared with that on the 6-phase rectifier of Fig. 3. As the author states, the accuracy of metering is increased by the reduction of the ripple, so that the figures given in Table 7 will be improved still further with increase of the number of phases. It is of interest to note that a change in design can improve matters in this direction, and I am disappointed that the paper does not enlarge on this subject.

The hysteresis effect on a mercury motor meter is well known, and the varying voltages experienced on traction loads may cause considerable errors unless precautions are taken when calibrating. To ensure a fair degree of accuracy, chart records of the busbar voltage and current have been taken in substations, so that meters are calibrated at varying voltages according to particular loads. A series of tests are taken with increasing and decreasing voltages at the various loads. To give an example, tests are carried out at one-quarter full load, the minimum and maximum voltages being 600 to 625 volts. Four readings are taken, two with increasing and two with decreasing voltage, the error of the meter being the average of these four readings. Recent tests of a batch of eight 1 000-amp. 600-volt mercury motor meters (see Tables A and B) gave the following results: Average error due to hysteresis, 0·7 per cent on all loads from full to one-twentieth full load; voltages, 600 and 625 volts. Differences between individual meters varied between 0·4 per cent and 1·3 per cent. Average error due to voltage variation: full load, at 600 and 625 volts, 0·75 per cent; one-twentieth load, at 600 and 625 volts, 0·3 per cent. The differences between individual meters varied between + 0·4 per cent and + 1·1 per cent at full load, and − 0·5 per cent and + 1·2 per cent at one-twentieth load, the one-twentieth-load readings being less affected owing to compensation increasing with voltage. A variation of 0·3 per cent will be obtained on the basis of the above figures if the working voltage of the rectifier is between 600 and 625 volts (assuming the e.h.t. voltage remains constant), the full-load voltage is 600 volts, and the one-twentieth load voltage is 625 volts.

There is one question which I should like to put to the author. In Fig. 3, which shows the ripple with a 6-phase rectifier, does 100 amps. represent full load on the rectifier?

Table A

Tests on Eight 1 000-amp. 600-volt Mercury Motor Meters (Shunted): Percentage Errors due to Hysteresis

Load	Voltage	1	2	3	4	5	6	7	8	Average
Full	600	0·6	0·4	0·8	0·9	0·7	1·2	1·2	1·3	0·7
1/20	600	0·5	0·5	0·6	0·7	0·7	0·6	0·7	0·4	0·6
Full	625	0·5	0·9	0·4	0·9	0·6	0·5	1·0	0·9	0·7
1/20	625	0·8	0·6	0·8	0·6	0·8	0·4	0·4	1·2	0·7

Table B

Percentage Errors due to Voltage Variations

Load	1	2	3	4	5	6	7	8	Average
Voltage increasing (tending to slow up meter)									
Full	+ 0·6	+ 0·9	+ 0·5	+ 1·1	+ 0·8	+ 0·3	+ 0·5	+ 0·5	+ 0·66
1/20	0·0	− 0·1	+ 0·6	+ 0·4	+ 0·8	+ 1·0	− 0·5	+ 0·6	+ 0·35
Voltage decreasing									
Full	+ 0·7	+ 0·4	+ 0·9	+ 1·1	+ 0·9	+ 1·0	+ 0·7	+ 0·9	+ 0·82
1/20	+ 0·3	− 0·2	+ 0·4	+ 0·4	+ 0·4	+ 1·2	− 0·2	− 0·2	+ 0·26

Percentage variation, 600–625 volts: Full load, 0·75; 1/20 full load, 0·3.

Mr. R. S. J. Spilsbury: The author's observations on reactive power metering are of great interest to me, since they emphasize the somewhat artificial nature of the quantity involved. The idea of reactive volt-amperes arises quite naturally from a simple definition of power factor as $VI \cos \phi$—itself an artificial conception in any except highly idealized circuits—but it has to be borne in mind that it has not the same physical basis as that of "real" power. The interest of reactive volt-amperes (or "vars") to the engineer arises from the fact that in 3-phase circuits in which the voltage and current are sinusoidal it is possible to obtain the total volt-amperes more accurately by measuring the watts and vars than by directly metering the desired quantity. Even here it has to be borne in mind that when the quantity required is the maximum demand uncertainties arise from the fact that the watt and var demands are not necessarily coincident, but the accuracy is usually sufficient for the purpose.

When, however, we turn to circuits in which the waveshape is not sinusoidal, we have a somewhat alarming chain of errors. In the first place, as the author shows, a normal reactive meter free from frequency errors does not measure the total reactive power in such circuits: in the second, the frequency error can be quite serious: in the third, the usual errors of some types of reactive meter due to unbalance, etc., are present: and in the fourth, we have the uncertainty with regard to coincidence of demands mentioned above. It seems that in such circumstances the best course will be to abandon this tortuous route to the desired goal and try to measure the total volt-amperes directly, preferably by some thermal method. Even a simple measurement of total ampere demand, with the assumption that the voltage did not vary, would often give a less error than the reactive-meter system.

Turning to the question of d.c. metering in rectifier circuits, the author mentions various cases in which errors arise from the fact that voltage circuits of meters are inductive, so that the a.c. component of the voltage flux is shifted in phase. This difficulty might be overcome by including in series with the inductive circuit a condenser shunted by a resistance. As is well known, such a composite circuit behaves as a non-inductive resistance up to quite high frequencies if the values of the components are properly chosen. Where the inductive circuit contains iron the compensation is not perfect under all conditions, but it should be quite satisfactory for the present purpose.

Dr. E. H. Rayner: There is one point on which I should like some information, and that is the errors of induction meters at the high-harmonic frequencies. These are ascribed to the induction of eddy currents in the disc. If this is their cause, would it help to use discs of higher resistivity?

As regards the question of d.c. integrating meters, there is the type in which the current goes through a disc in mercury, and, while this is a simple design, with large currents the difficulties are very considerable,

partly on account of the use of shunts, and the very large current taken by the meter compared with indicating instruments, so that contact resistances, etc., are relatively very much more important. One knows by experience how difficult it is to get the errors down to what they might be, except by special and often lengthy adjustments. It is a question of either using a shunt in the current circuit, which has to be done with mercury meters, or passing all the current through the meter coil, which can be done in meters which do not use mercury. Both methods have their advantages and disadvantages. An additional factor arises from the errors due to the unsteady character of the d.c. voltage or current. A method of meeting this condition has been shown us—a mumetal core, which has a very low hysteresis factor. This promises to be of distinct value.

I have no doubt that the advent of the mercury rectifier will give a new impetus to the improvement of the d.c. integrating watt-hour meter.

Mr. G. H. Fowler: I should like to ask whether the figures given in Table 7 will apply equally well where the 6-phase rectifier, instead of having six anodes in one bulb, is built up of two 3-phase rectifiers arranged as a 6-phase group. I have a feeling that this will not be the case, because it seems that the harmonics are smoothed out to a considerable extent by the overlapping caused by the conduction of the arc in a 6-phase rectifier. Perhaps the author will say whether, in the tests described, a 6-phase rectifier was used, or two 3-phase rectifiers combined. Can he suggest any possible figures for the alternative arrangement?

Mr. C. W. Pike: In practice I have found the apparent efficiency of mercury-arc convertors to be unduly high, even higher than optimistic manufacturers state. Fortunately the a.c. measurement is taken on the primary side and, as harmonics decrease in amplitude as their order increases, it is only the lower ones which become a nuisance to metering. The great difficulty in this respect seems to be that we may get the voltage wave and the current wave to contain different frequencies, and, as different frequencies cannot interact, the metering will be inaccurate to that extent.

As regards d.c. meters, the clock type appears to give us the best results. In the first instance I think this is due to the fact that it has no iron in its circuit, and secondly there is the important consideration that if a whole-current type clock-meter is used there will be little or no temperature error. A suitably designed clock meter is accurate on direct current and also up to quite high frequencies, and it seems to me that, taken over a period, which is what usually happens, the average result shown by a clock meter is far superior to that given by any other type.

With respect to systems of charging, where maximum demand enters into the question, in my own undertaking we have a type of consumer who is very difficult to deal with. We are gradually changing over from d.c. to a.c. supply, and unfortunately we have very large numbers of power consumers, who are very costly to change over. What we are proposing to do, therefore, is to change over their lighting and heating to alternating current, leaving their power loads on direct current. We shall probably do this by installing mercury-arc rectifiers. In such a case the metering has to be done on the primary side. Maximum demand, as far as the undertaking is concerned, is mainly judged by the thermal effects on cables and other apparatus, and therefore it seems to me that the best and fairest method is to use a thermal demand indicator. Incidentally, although it may not give the kVA demand accurately, it gives an accurate value for the ampere demand, and this is something quite tangible on which a consumer can be charged.

Mr. E. W. Hill: One would expect on general theoretical grounds that the clock-type meter would act reasonably well even on direct current distorted by a pronounced ripple. The voltage circuit, especially for fairly high voltages, includes a high, non-inductive, swamping resistance and therefore has a negligible inductance. As Mr. Pike pointed out, the whole-current pattern meter has a negligible temperature coefficient. The meter in consequence seems to have all the qualities which one would deem to be desirable for measuring either direct or alternating currents in a single instrument. It has been found capable of doing this for the usual power frequencies, but I have no information as to its performance at high frequencies. The shunted-type meter might not be expected to give such good results because, as several speakers have pointed out, the time-constants of the shunt and of the meter's series element are different. This particular difficulty is avoided by the use of the whole-current meter, but others might be encountered. For example, it is quite practicable to make a clock-type meter for 1 000 amperes whole-current, but there might be, at high frequencies, troubles due to eddy currents in the rather massive block of copper which is used for the main coil. All the same, however, I think that the whole-current meter would be the thing to try. The sizes up to 4 000 amperes have been made for traction work, and as such sizes are exceedingly sensitive the results have been very good.

If I may dissent from Mr. Howarth's opinion, I would say that I think that, after all, the question of power factor and maximum kVA does play a large part in our consideration of the economics of energy transfer. For a given energy flow, it does matter a great deal from the economic point of view whether the cables, transformers, and switchgear, have to carry 20 or 30 per cent more current than is needed, for example.

What emerges clearly from the paper is that we can measure, with the ordinary induction-type meter, the a.c. input accurately as regards power, but as regards the power factor and the total volt-amperes or kVA we shall probably have to revise our ideas. It seems as though with badly-distorted wave-forms we cannot obtain an assessment of the total kVA by using the hypotenuse of the energy triangle whose other two constituents represent the actual power and the reactive power. This method must be discarded on account of the distortion-power term P_d, which it does not seem possible to subdue by any ordinary methods of measurement.

As to the behaviour of Hill–Shotter kVA maximum-demand indicators on bad wave-forms, the only definite information I have available concerns one of the 3-phase declared-voltage pattern (Type A3), which was tested when used on a neon sign of which the current wave had the following characteristics: The harmonic constituents

were 12·8 per cent third harmonic, 1·5 per cent fifth harmonic, 1·4 per cent seventh harmonic: the form factor of the current was 1·1446, and its peak factor was 1·56. Under these conditions the instrument was found to be indicating 1·5 per cent higher than on a normal sine wave.

Dr. L. G. A. Sims: I should like to make some comments on the measurement of kVA, and particularly on the measurement of the current term involved. The author makes it quite clear that there are two problems to be considered here. The first is the frequency characteristic of the meter, which to some extent is under our control. The second is the registration of mean values of products of two different frequencies, a matter which is not under our control and never will be. Is it possible, therefore, to concentrate attention entirely on the distorted current rather than on the volt-amperes? Logically, this seems to be the thing to do. Morally, it may not be quite fair to the consumer, and the author may care to say whether or not the injustice to the consumer in measuring only the current in the line is greater than the error involved in attempting to evaluate the kVA. If it is, I would ask whether there is any value in the fact that it is readily possible to separate out the whole harmonic content of the distorted current. It seems to me that it might be possible to provide an auxiliary driving torque by means of such a separated harmonic current and so approach more nearly to the solution of the practical, if not of the theoretical, difficulty to which the author draws attention.

My final point is concerned with terminology. It seems a pity that we have to use the word "reactive" to refer to a series of harmonics with unknown or varying phases. If we could reserve that term for the sinusoidal quadrature component, and include all the harmonics in some other term, not yet used, the outlook on this problem would be somewhat simpler from the outset.

Dr.-Ing. R. Feinberg (*communicated*): The author gives in Appendix 1 a rather complicated formula for the power factor of a p-phase rectifier; I recently showed* that the phase angle ϕ for a p-phase rectifier is given by the expression

$$\tan \phi = -\frac{\mu - \sin \mu \, . \, \cos (2\alpha + \mu)}{\cos^2 \alpha - \cos^2 (\alpha + \mu)}$$

where μ is the angle of overlap and α the angle of grid retardation. The minus sign indicates that the reactive power is inductive. The power factor is given by

$$\cos \phi = \frac{1}{\sqrt{(1 + \tan^2 \phi)}}$$

Mr. J. L. Ferns (*communicated*): It is unfortunate that the author has arrived at some very far-reaching conclusions without having at his command all the requisite data—in spite of his apparently unrivalled opportunities for making suitable experiments.

He omits to consider the pendulum meter, and in view of its inherent ability to measure either direct or alternating current this omission is very striking. The mercury motor and Thomson dynamometer meters have extremely serious mechanical drawbacks which more than offset the ability to take spot readings of the load, or the absence of complicated clockwork. I feel sure that the majority of meter engineers would be more interested in learning the effect of bad wave-shapes on the pendulum meter, rather than on the mercury or Thomson types.

Another mistake is to obtain results for one particular type of induction meter and base general conclusions on such data. The author also omits consideration of the saturating effects of, or the braking torques exerted by, all the fluxes of other frequencies, when dealing with the meter error for a particular frequency.

More important still, he dismisses the question of accurate kVA measurement without any mention of the Hill–Shotter or the thermal or other types of maximum-demand indicator. Thus, although his conclusions may possibly be correct, the data in the paper by no means substantiate such conclusions. In view of these omissions, the author's hope that the paper will be a guide in choosing meters for rectifiers is unfortunately not likely to be fulfilled.

Reactive kVA and kVAh are naturally meaningless quantities as soon as the wave-shape deviates from the sine wave, but kVA demand is always a quantity which can be definitely measured. I am rather surprised, therefore, that the question of kVA measurement is so summarily dismissed by the author. I firmly believe that it is possible to make a kVA maximum-demand indicator without the exponential-law drawback of the ordinary thermal type of instrument, and I should like to ask the author whether he considered the possibilities of such an instrument before arriving at the conclusions expressed in the paper.

Mr. J. C. Read (*communicated*): The most important part of the paper is that which deals with the accuracy of induction disc meters in metering the active-energy a.c. input to 6-phase rectifiers. I should like to ask whether the author considers that some induction disc meters on the market may have errors, when metering rectifier input energy, considerably larger than the figure of 0·5 per cent which he gives as the probable limit of error in practice. I have known at least two cases where there was evidence that such meters were reading high by as much as about 2 per cent, after great care had been taken to calibrate them and their transformers on sinusoidal normal frequency; so that it would seem possible that not all commercial meters are quite as accurate on these wave-forms as those which the author has tested.

The paper seems to suggest that the errors in metering the active a.c. input are due to the meter reading low as regards its response to the active harmonic power fed back by the rectifier to the resistance in the a.c. supply system. It can be shown, however, that even if the response of the meter to frequencies above 50 cycles per sec. were absolutely zero, the error due to this cause, with the highest amount of a.c. supply resistance normally met with in practice, could never exceed 0·1 to 0·3 per cent in the case of 6-phase rectifiers. It seems necessary to look for other sources of error.

The rectifier feeds back to the a.c. system, not only active harmonic power due to the harmonic losses in the resistance of the a.c. supply, but also reactive harmonic power due to the current harmonics flowing through the reactance of the a.c. supply. This reactive harmonic

* *Elektrotechnik und Maschinenbau*, 1937, vol. 35, p. 137.

power is usually many times larger than the active harmonic power. It would seem possible that an error may occur in metering, through the reactive harmonic power affecting the reading of the meter, due to phase-angle errors in the meter at high frequencies. The phase-angle errors indicated in Fig. 4 would apparently permit such a source of error, and I should like to know whether the author considers that this error may be appreciable. It would seem from his paper that he does anticipate such a possibility, as the curves in Fig. 6 are plotted against line reactance instead of against line resistance.

With regard to the problem of metering the true power factor, the author suggests using sine- and cosine-meter readings to determine $\cos\phi$, the power factor of the fundamental current; and then obtaining the true power factor by an arbitrary correction of the $\cos\phi$ reading. While this expedient may serve in special cases, I think the better policy is to recognize that the true power factor is of little practical interest, the quantity that really affects the supply system being, in practically all cases, not this but $\cos\phi$. The reason why $\cos\phi$ is the quantity which is of interest to the a.c. supply system is that the effect of the harmonics rapidly becomes negligible when the rectifier is operated in parallel with other loads on the same a.c. system. It may readily be shown that, in all practical cases, it is $\cos\phi$, and not the true power factor of the rectifier, which determines how much effect the addition of the rectifier to a given a.c. system will have on the power factor and losses in that system. This is a fortunate fact, since $\cos\phi$ can be determined from sine- and cosine-meter readings with ample accuracy.

There are two minor matters of terminology which I should like to mention. One is that the author might perhaps consider it worth while, when finally revising the paper for the *Journal*, to denote the angle of overlap by u instead of μ, thus falling into line with practically all other writers on the subject. The other point is that he uses the term " reactive power " to denote both P_R and P_T. It is unusual to describe the product of a current and a voltage of different frequency as " reactive power "; and I suggest that P_T could be better described as the " total wattless power," leaving the term reactive power restricted to its more commonly-understood meaning, namely the product of a voltage and a current of the same frequency, in quadrature with one another, i.e. P_R. Where I have used the term " reactive power," I have used it with this latter meaning.

Mr. G. Wall also took part in this discussion. The substance of his remarks will be found in the report of the Manchester discussion (see page 274).

[The author's reply to this discussion will be found on page 275.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 6TH APRIL, 1937

Mr. J. L. Carr: At first sight some of the particulars given in the paper seem to indicate that serious errors may be experienced in the metering of rectifier supplies, but a little further examination will probably show that in practice the errors are not likely to be quite as serious as expected. The author's remark that the distortion shown on the curves in the paper is probably considerably worse than may be expected in practice, is reassuring.

It is fortunate that for other reasons the use of a rectifier with a low number of anodes is not favoured in appreciable sizes. The particulars given for induction meters indicate that with an increasing number of electrodes the errors decrease very appreciably. For example, for a 3-phase rectifier the expected error is about 1 per cent; and for a 6-phase rectifier 0·5 per cent.

The question of radio interference caused by rectifiers is one of considerable importance. Many supply undertakings will not have the temerity to put in fairly large rectifiers for, say, trolley-bus purposes, without careful consideration of this effect. If a 6-phase rectifier is employed it will almost certainly be smoothed; but in the majority of cases unsmoothed 12-phase rectification would probably be employed. With 12-phase rectification the expected metering errors are likely to be, as the author remarked, almost negligible, neglecting for the moment the question of the reactive metering. Rectifiers with a small number of electrodes are probably not used except as part of another supply. In the change-over from direct to alternating current, one or more appliances may be supplied from single-phase rectifiers, but the majority of the load is taken from the 3-phase supply. In such cases the effective distortion is reduced very considerably, because the rectifiers form only a small proportion of the total load.

It would have been interesting to have had a little more information about the effects of rectifier supplies on other types of meters. For example, the clock-type meter at one time was quite extensively used on a.c. circuits; and it is free from many of the objections of the induction and the Thomson meters. For ordinary 3-phase supplies the clock-type meter is rather complicated in regard to maintenance, and has practically fallen into disuse; but for d.c. circuits it is still held, in many quarters, to provide the most precise form of watt-hour metering available commercially. The inductance of the voltage element is small compared with the total resistance; and no iron is employed in its operating parts. Errors due to distortion of wave-form are likely to be small, and probably negligible for 12-phase rectification.

The power factor for a 3-phase rectifier on distorted supply is shown as 71 per cent, and for a 6-phase rectifier as 89 per cent (Table 4). In many cases—at least with 6-phase and 12-phase rectifiers—the power factor will probably be in excess of the usual datum figure of 80 per cent for commercial supplies. Reactive metering does not, therefore, appear necessary. It is rather important to note that, in the author's view, reactive-kVA metering is altogether unsatisfactory for rectifier supplies.

Mr. O. Howarth: It seems to me that in the future even the house service meter will have to register more on distorted wave-forms than it does at present; wireless sets, for example, do not take sinusoidal currents. The d.c. problem is perhaps more difficult than the a.c. problem. Distorted currents and voltages are becoming

usual, and the d.c. meter has not in the past been adapted for them at all.

In Fig. 7 the author gives some load/error curves for meters; he appears to have taken his tests on a single-phase meter, putting it first in one and then in the other position in a 3-phase system, using the conventional two-wattmeter method. He refers to the bridge piece affecting the curve at the higher loads; I think, however, that the bridge piece is not usually present in a polyphase meter, there being no provision for overload characteristics on 2-element meters. If this is the case, he has not made his test on the right type of meter.

There are other factors which combine with these distorted waves to influence the behaviour of induction meters—temperature, self-heating, and voltage variation. It would be useful if the author could continue his investigation with a view to determining whether the effects with distorted waves are similar to those with sine waves.

One appreciates that the author could not be expected to examine the effects of distorted waves on meters other than those manufactured by the firm with which he is connected, but had he done so his results might have been different. Other manufacturers might also investigate the characteristics of their meters more rigorously than they do at present.

Mr. A. E. Moore: It is many years since I did some experimental work on the effect of wave-form on the accuracy of induction watt-hour meters. About that time, in 1908–10, the same meter when tested in different laboratories often gave seriously different results, and it was frequently assumed that the differences were due to the meter being tested with different wave-shapes. At that time also it was being asked whether integrating meters registered accurately on varying loads. This matter was investigated by Robertson* and by Melsom and Eastland.† In general, the wave-forms of modern a.c. supplies are approximately sinusoidal, and until more recently one heard very little about the operation of meters on distorted waves. The introduction of arc rectifiers, however, has brought about large deviations from sinusoidal conditions, and questions relating to the accuracy of supply meters on these waves are again being raised.

So far as the author's experiments with the Thomson type of meter (or "ironless dynamometer") are concerned, we should expect good agreement between the Thomson meter and the standard wattmeter because they are of the same type. It is rather a pity that the integrating form of the dynamometer meter cannot be constructed to register with the same precision as does the indicating instrument. The integrating type is fundamentally accurate, but the difficulties which arise owing to the commutator, etc., are great, and for this reason and others the induction meter has many advantages over it.

The statement on page 259 "It is of interest to note that a meter having a purely resistive disc . . . would have a performance independent of frequency" is quite correct, and when I am dealing with the theory of induction meters I try to get the students to see that the meter under those conditions would not only be independent of frequency but would also register correctly on direct current. Those conditions are, however, quite hypothetical. For example, it would be impossible to induce a current in "a purely resistive disc," and therefore the meter would not work. It is instructive, however, to study the behaviour of the meter under those conditions in an attempt to visualize how near we can approach the construction of the ideal instrument.

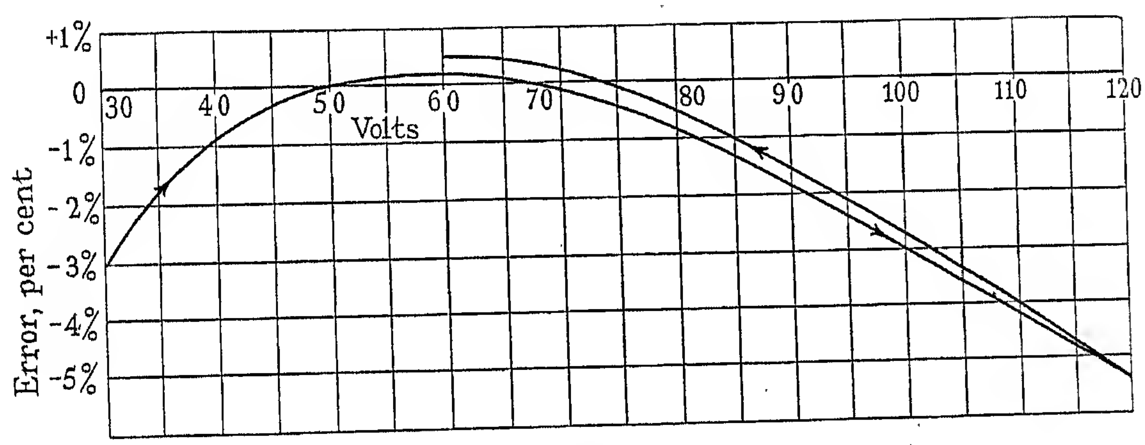


Fig. A

Mr. Howarth raised the question whether the author had made tests on meters other than those manufactured by the firm with which he is associated. This afternoon I got an assistant to test a modern meter of another make, and the results agree very well with those given by the author. In the experiments carried out by Mr. Ratcliff and myself in 1910,* on distorted wave-forms, one meter showed an error of 0·1 per cent with inductive load as against 6·6 per cent with non-inductive load. This difference with change of power factor is almost certainly due to the harmonic power being reduced very much more rapidly than the fundamental power, and I think that that result probably explains why the author has found such small errors. He refers to the two-wattmeter method of measuring power and reminds us that the accuracy of measurement of the total power may be quite good although the wattmeter measuring in the low-power-factor phase may have a quite large error. I think a similar explanation tells us what is happening in the case of his measurements with distorted waves. The error in the meter at the harmonic frequencies is very large

* *Journal I.E.E.*, 1912, vol. 49, p. 489.
† *Ibid.*, 1912, vol. 49, p. 465.

* *Journal I.E.E.*, 1911, vol. 47, p. 3.

when expressed as a percentage of the harmonic power, but the harmonic power constitutes only a small part of the total power, the major part of which is at fundamental frequency. I think, however, that one ought to be careful, not to say that the meter will register accurately under all conditions involved with these rectifier circuits, but to examine each case to see whether the conditions are such as to make the harmonic power a very small proportion of the whole.

Mr. G. Wall: The author, in referring to d.c. output measurements, stresses the effect of under-registration in mercury motor meters due to the inductance of the voltage circuit. My experience is that the most serious source of error with this type of meter is not under-registration but over-registration, due to residual magnetism in the iron circuit of the meter, probably arising from surges in the line, which are absorbed in a motor-generator but not in a rectifier. I have observed a speed

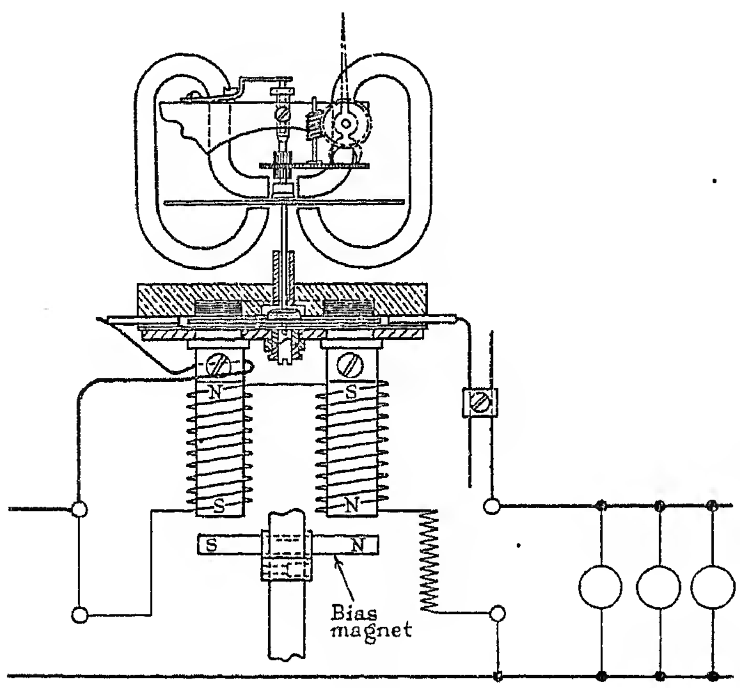


Fig. B

increase of 5 to 6 per cent in a mercury motor meter after the application of a voltage surge of double line voltage. Some tests recently made show that by the use of mumetal in place of stalloy in the voltage magnet circuit, and a slight bias from a permanent magnet, this residual magnetism can be brought within allowable meter errors. In the installation of d.c. meters care should be taken either to place them at a distance from conductors carrying large direct currents or to shield them from external magnetic fields.

This paper shows that the problem of measuring the efficiency of mercury-arc rectifiers seems capable of solution if there is collaboration between the users of rectifiers and meter designers. I would suggest that two 6-phase rectifiers and their transformers be used in parallel, so connected as to form a 12-phase rectifier.

Fig. A shows a curve taken a few days ago on a 20-amp. 60-volt mercury motor meter (Fig. B); it indicates an error within 2 per cent from 40 to 80 volts, and with a transient voltage up to 120 volts the meter is slightly faster on descending to 60 volts. From these results it seems possible to overcome the defects exhibited by the mercury motor meter when subjected to over-voltages or surge voltages.

Mr. M. Whitehead: Reference is made in the Summary to " induction-type and motor-type " meters and later to " motor- and mercury-type " meters. All these meters are motor meters, and it would have been better had the author used the term " commutator meter " in place of his " motor meter."

About 18 months ago some tests were made on a rectifier supply with an induction meter of different manufacture from that of the meters mentioned in the paper, and the results agree very well with those now given by the author. The rectifier had three phases, the load on the meter was 90 per cent of its rated load, and the error was $+ 0\cdot 8$ per cent.

Further information on the subject is contained in an article by A. Asta on the behaviour of induction-type meters in mercury-vapour rectifier circuits.* In this article it is stated that errors up to $+ 4\cdot 0$ per cent may occur.

Finally, I think the author might have included some information relating to the influence of instrument transformers. The probability is that their effect is very small, but it would be of interest to have this confirmed.

Mr. A. M. Strickland: Rectifiers may in the future be further developed on very small supplies, and it seems desirable that one should feel certain that all the induction meters one can use will satisfy the requirements and still read accurately. For instance, household appliances might be provided which would split the wave up into three times or five times normal frequency, and the work at the higher frequencies will become highly important.

On page 259 the author remarks " The nature of the effect of frequency on the performance of induction meters was well understood from the work of previous investigators. . . ." It would be as well to make it clear that this work only covered a limited range (from about 25 to 80 cycles per sec.) on 50-cycle meters; I have not seen similar curves for high-frequency effects. It is perhaps unfortunate that the author carried out his tests with only one type of meter, and I would suggest that he has hardly picked on the most appropriate type. Table C shows some results which I have obtained on various meters at higher frequencies, and it is interesting to see how they fall into line with those given by the author. The features of the type M meter, of low-resistance voltage coil and liberal design, will be noted.

On page 261 the author calls for high accuracy in adjustment, and I agree that still higher accuracy than we obtain to-day will be desirable to deal with rectifier wave-forms. Would the author care to commit himself to the statement that for accountancy purposes it would appear to be desirable that the metering should always be done on the a.c. side, owing to the complications and high cost of d.c. meters? The costing could be made for the works distribution accountancy with cheaper if slightly less accurate d.c. metering, but not for billing purposes. It would appear that to get good metering on the d.c. side is going to be very expensive when large outputs have to be metered.

Mr. W. Fennell: I do not think there are any figures

* *L'Elettrotecnica*, 1933, vol. 20, p. 458.

Table C

TESTS ON NORMALLY-CORRECT 50-CYCLE INDUCTION METERS AT HIGH FREQUENCIES

Meter type	Voltage-coil resistance	Weight	Percentage registration at unity p.f.			
			250 cycles	500 cycles		
			Full load	Full load	$\frac{1}{5}$ load	$\frac{1}{10}$ load
	ohms	lb.	%	%	%	%
Author's type NE (see Fig. 4)	700	5	53	25	—	—
T	2 500	$4\frac{1}{2}$	49	25	19	19
E	1 500	$6\frac{1}{2}$	52	22	18	16
L	1 200	4	48	20	15	15
M	350	$8\frac{1}{4}$	81	56	47	45

in the paper for the probable errors in the case of a single-phase rectifier combined with a single-phase meter. I know of one case where there is a supply of perhaps 30 kW, of which at least 20 kW are in that form. There are many single-phase rectifiers in use on wireless sets, and some of those sets are installed on the premises of small consumers and in connection with small meters; so the matter of single-phase error may be more important than it at first appears.

One point that interests me is the further discredit that this paper will throw upon the metering of power, expecially where there are rectifiers, on the basis of a charge per kVA plus a charge per unit. Obviously, the increased cost to the supplier due to a lower power factor than unity is not in proportion to the power factor. Apparently in addition to this departure from equity there is the inaccuracy in the kVA meter. This is a point which those who are buying in bulk per kVA or who are large power consumers should investigate.

I do not know how the Central Board record whether an undertaking has fallen below 85 per cent power factor, the point where the penalty commences; if it is by observing the power-factor indicator the error in this may be important should there be a good many rectifiers in conection with the circuit. Can the author state the probable errors of indicating instruments?

Clock-type meters have the advantage that they have no starting current. In other words, they are absolutely accurate at and near no load; their error increases in proportion to the load, according to a straight-line law, within reasonable limits.

THE AUTHOR'S REPLY TO THE DISCUSSIONS BEFORE THE METER AND INSTRUMENT SECTION AND BEFORE THE NORTH-WESTERN CENTRE

Dr. C. Dannatt (*in reply*): Several speakers have suggested that tests on a single example of a meter of any given type are not sufficient on which to base general conclusions. This is, of course, obvious, and no such claim is made in the paper. The examples taken were chosen in every case to show the nature of possible errors, and to emphasize those characteristics on which a user of meters in rectifier circuits might reasonably expect to receive information from the manufacturer.

Mr. Pick and Mr. Fawssett both point out that in practice mercury meters read high in rectifier output circuits. As stated in the paper, this is due to hysteresis effects in the iron of the voltage circuit. The subject was not enlarged upon, because the trouble is not peculiar to rectifier circuits. Mr. Wall has made a valuable contribution to the discussion, since he has shown how the mercury meter may be made almost immune from error due to hysteresis. Mr. Quenzer gives some interesting figures on hysteresis errors in mercury meters, over a voltage range of 600 to 625 volts. Errors much larger than those he mentions are observed in practice; these are due to transient increases of voltage much larger than those due to ordinary regulation.

Considerable discussion has turned round the clock meter. It is, I think, clear that the frequency error of this type of meter is calculable from the data of the voltage circuit of the meter and could be made quite negligible in practice. There seems no doubt that the whole-current type of clock meter is well adapted to output metering in rectifier circuits, provided users are prepared to put up with the cost and the maintenance involved.

Dr. Sims and Mr. Read both point out that the term "reactive power" is best reserved for the quantity I have denoted by P_R, and Mr. Read further suggests that a more suitable term for P_T is "total wattless power." I am in agreement with these views and I have altered the paper accordingly for the *Journal*. There is a consensus of opinion that what Mr. Spilsbury has aptly termed the "tortuous route" to kVA measurement—via sine and cosine meter readings and the introduction of power-factor measurement—is best avoided in rectifier circuits.

It was in the hope of fostering that view that I devoted a section of the paper to the question. Various opinions have been expressed with regard to the desirability of tariffs based on kVA measurement, but that is a matter outside the scope of the present paper. Several speakers have, however, expressed the view that kVA, when it is required, would best be determined by a thermal method, but such a solution awaits the production of a meter which takes correct account of the voltage variation, and also does not suffer from the exponential law of heating. The latter difficulty still exists even if the simple thermal demand is taken as a basis for formulating a tariff, as has been advocated by several speakers. Mr. Hill has quoted an example of the results obtained with a Hill-Shotter maximum-demand meter in the case of a distorted load. It would be very interesting if he could obtain and publish some further data on the performance of this type of meter in rectifier circuits.

Mr. Pick's experience in measuring the efficiency of rectifiers by means of input and output meters is extremely valuable, although a little disturbing. It would appear that he has been chiefly troubled by the influence of stray fields and by hysteresis effects in the d.c. meters. With regard to the measurement of regenerated power, it would be necessary to install an extra meter with a ratchet device to permit registration in one direction only. Mr. Fawssett rightly points out that the error of a meter recording a.c. energy on the output side of a rectifier depends on the power factor of the a.c. energy. Mr. Spilsbury's suggestion for correcting the potential circuit of d.c. meters by condenser and resistance is very sound and would prevent the difficulty mentioned by Mr. Fawssett. In reply to Dr. Rayner, there is no doubt that a higher-resistivity disc in an induction meter would improve the performance at high frequencies, but this would be done at the expense of poorer performance at 50 cycles, and it must be remembered that by far the largest part of the energy in rectifier circuits is supplied at 50 cycles.

In reply to Mr. Fowler, the figures in Table 7 relate to a 6-anode rectifier. A group of two 3-anode rectifiers with interphase transformer would probably have slightly less ripple. In reply to Mr. Quenzer regarding Fig. 3, at 100 amperes the reactance of the transformer was about 5 %.

Dr. Feinberg will find that his expression for $\tan \phi$ reduces to the same value as I have given for $\cos \phi_1$.

Mr. Howarth and Mr. Ferns both refer to the effect of the saturating plate in the induction meter. It was shown during the course of the experiments that up to full load on the meter the discrepancy in error between sinusoidal and distorted loads was not affected appreciably by the presence of the plate. Mr. Ferns refers to braking torque by fluxes of other frequencies in the case of the induction meter. He seems to be under the impression that an energy loss in the disc due to such fluxes must result in a braking torque. A little thought should convince him that such is not the case.

Mr. Read's estimate of the loss in the series resistances of rectifier circuits is very interesting. I agree with him that there is a feed-back of reactive harmonic power from the rectifier, and the frequency error for this has been taken into account in estimating the errors in Table 6.

I agree with Mr. Moore that the real difficulty with the Thomson meter lies in its commutator. If this could be improved the meter would find many more applications. Mr. Moore rightly concludes that the percentage error of the induction meter, as far as harmonic power is concerned, is very high, and that the overall error is small only because the harmonic power is a small percentage of the total power. Mr. Wall's suggestion that suitable choice of connections when rectifiers run in parallel should be used to simplify the metering problem, is very sound; in addition, such a procedure may eliminate other difficulties in network operation which arise from the presence of harmonic currents.

Mr. Whitehead raises the question of instrument-transformer performance in distorted circuits. This is a problem which merits further investigation, although it is not likely to be of serious importance as far as energy metering is concerned, since, as has already been pointed out, most of the energy is supplied at fundamental frequency. Mr. Strickland suggests that better performance could be obtained at high frequency by modification of the induction-meter design. This may be true, but it would be done at the expense of either desirable characteristics at fundamental frequency or else at the expense of extra weight, dimensions, and cost. I am not prepared to say that metering in a rectifier circuit should always be carried out on the a.c. side. Each case must be settled on its merits.

In reply to Mr. Fennell, I regret there are no results in the paper relating to single-phase rectifiers, but I think it is safe to assume from the data of Table 1 and Fig. 4 that the errors would be of the same order as for 3-phase rectifiers. With regard to indicating power-factor meters, it would be expected that most types would record the value of the displacement factor of the circuit, that is $\cos \phi_1$, and not the true power factor.

A VARIABLE AIR CONDENSER WITH ADJUSTABLE COMPENSATION FOR TEMPERATURE*

By H. A. THOMAS, D.Sc., Associate Member.

[From the National Physical Laboratory.]

(*Paper first received 16th March and in final form 26th May, 1937.*)

SUMMARY

The paper forms a natural continuation of an earlier investigation of the electrical stability of condensers and the development of satisfactory means of obtaining compensation for temperature variation. It has been shown in a previous paper that such compensation can readily be obtained for slow temperature-changes, but that great care is necessary in matching the thermal masses of the various parts if the temperature-changes are rapid. By applying the results of this previous analysis, a condenser of reasonable size has been developed which is compensated for temperature-changes as rapid as 7 deg. C. per minute.

Special design features are introduced to produce this result, the most noticeable of which are the use of spring-loaded steel balls in place of plain bearings and the inversion of the normal electrical connections to rotor and stator, this latter alteration being adopted to eliminate difficulties which arise with an earthed screening case.

Electrical tests of the performance under varying conditions of temperature-change show that the temperature coefficient of capacitance can be adjusted to have any value between the limits + 80 and − 80 parts in a million per deg. C. and therefore that the coefficient can be so adjusted as to compensate for the inductance coefficient of the associated inductance coil. The variation of the resultant frequency coefficient of the complete circuit with change of oscillation frequency is not large, and the transient variations do not exceed 10 parts in a million per deg. C. for temperature-changes at a rate of 7 deg. C. per minute.

(1) PRELIMINARY OBSERVATIONS

The contents of a recently-published paper† have indicated the conditions which must be fulfilled to produce a satisfactory temperature-compensated condenser. This paper contains a description of two condensers which gave a good electrical performance for slow temperature-changes, but it is pointed out that, for rapid thermal variations, considerably more care must be devoted to the design to satisfy the required thermal conditions.

These conditions have been determined, and in condenser No. 2,‡ a preliminary attempt was made to satisfy them in practice. The results of tests on this condenser showed that further improvement was necessary to obtain compensation for very rapid temperature-changes. Furthermore, condensers Nos. 1 and 2 were both designed without restriction of weight and size, with the primary object of testing the efficacy of the design principles. In view of the comparative success obtained with these two condensers, it was considered advisable to apply the same principles to the design of a condenser of more practical dimensions suitable for use in a receiver or small transmitter.

Previous work had revealed the difficulty of compensating for the expansion and distortion of the earthed metal case surrounding the plate assembly. The thermal capacity of the usual type of cylindrical case is very different from that of either plate assembly owing to its large area and small mass; its mechanical rigidity is also much inferior to that of the condenser itself. If a conventional type of case is adopted, it must appreciably increase the overall dimensions of the assembly, and if the effects of case expansion are reduced to a negligible amount this increase in size is excessive.

With the object of eliminating the difficulty of designing a satisfactory case, it was decided to depart from the usual practice and to make the stator the earthed electrode system. This modification makes the design of the stator and case a comparatively simple matter, since the two form one earthed system. The obvious objection to this constructional inversion is the difficulty of insulating, locating, and driving the rotor, but in view of the admitted inadequacy of the location provided by most ordinary plain bearings, and the fact that some alternative means of turning the rotor is desirable for a condenser of high secular stability, this objection was not considered unsurmountable.

(2) DESIGN OF CONDENSER

The design of the new condenser (referred to as No. 3) is shown in Fig. 1. The earthed stator plates (8) are let into and soldered into grooves cut internally in the cylinder (6). The rotor plates (7) are soldered to the centre shaft and the location of this shaft is provided in the following manner. At the left-hand end, the shaft is held in contact with two steel balls and a quartz washer (4). The location provided by the conical recess in the shaft and end plate together with the countersunk holes in the quartz washer is excellent if lateral rocking of the washer is prevented by means of the light clamping ring (3). The pressure required to maintain definite location is obtained by the steel spring (1) acting through the two rods (5), which are fixed to and insulated from the rotor assembly by small quartz washers. With a tension on this spring sufficient to maintain contact at all settings

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† H. A. THOMAS: "The Electrical Stability of Condensers," *Journal I.E.E.*, 1936, vol. 79, p. 297.

‡ *Ibid.*

of the condenser, the friction introduced by the steel ball (2) and the locating balls and washer is no greater than that given by a good plain bearing. Consequently, by attaching a knob and pointer to the spring plate (1), the rods (5) are made to serve the dual purpose of locating and driving the rotor.

Location of the right-hand end of the rotor is provided by an arrangement of steel balls and a quartz washer similar to that at the left-hand end. Any differential expansion which may take place between the stator cylinder (6) and the rotor shaft is taken up by the sliding piston (14), in which is situated the locating conical recess. This piston is provided with a light spring of sufficient strength to give precise location without applying any appreciable bending moment to the rotor shaft. The air-gaps are arranged to be all approximately equal and, since the whole assembly is made of the same metal, the temperature coefficient of capacitance should be sensibly equal to the coefficient of expansion of the metal. The electrical connection to this rotor spindle consists of a nut working on a thread and connected to a quartz-insulated terminal by a flexible rod.

Compensation for temperature-change is accomplished in the following manner. A special stator plate (9) is fixed to a steel tube (12), which in turn is clamped to the housing (13). This housing can be moved slightly by means of the screwed compensating ring (11) and clamped in any position by six screws. By varying the position of this end plate with respect to the rotor plate (10), a large range of capacitance-change can be obtained in this end cell. For example, in the position shown in the diagram, where the air-gap is small on the left of the plate (9) and large on its right-hand face, the differential expansion between the steel tube and the brass housing gives rise to a negative temperature-coefficient, whereas, if the gap dimensions are reversed by turning the screwed ring (11), the coefficient can be made positive. Movement of the housing (13) does not alter the location of the rotor, since the piston (14) always maintains contact between the rotor shaft and the steel balls.

A number of thermal tests were made to ascertain the thermal properties of various rotor and stator assemblies, and, as a result of these tests, the thermal constants of these parts were adjusted to give compensation for rapid changes of temperature. The degree of success achieved can be judged by reference to the results of measurement given in the next section of the paper. A metal gauze cage covers the large air holes in the stator cylinder (6), completely shielding the rotor plates without appreciably affecting the thermal properties. The overall length and diameter of the condenser are 7 in. and 4 in. respectively; the weight of the complete assembly is 7 lb. (3·2 kg.). The capacitance range is 47–265 $\mu\mu$F. The present design makes use of a symmetrical stator and rotor system giving a 90° rotor movement. If it is desired to use a movement of 180°, this can of course be accomplished by using a conventional rotor and stator assembly. In this case the dimensions would probably need slight modification to give the thermal equilibrium obtained in the present design.

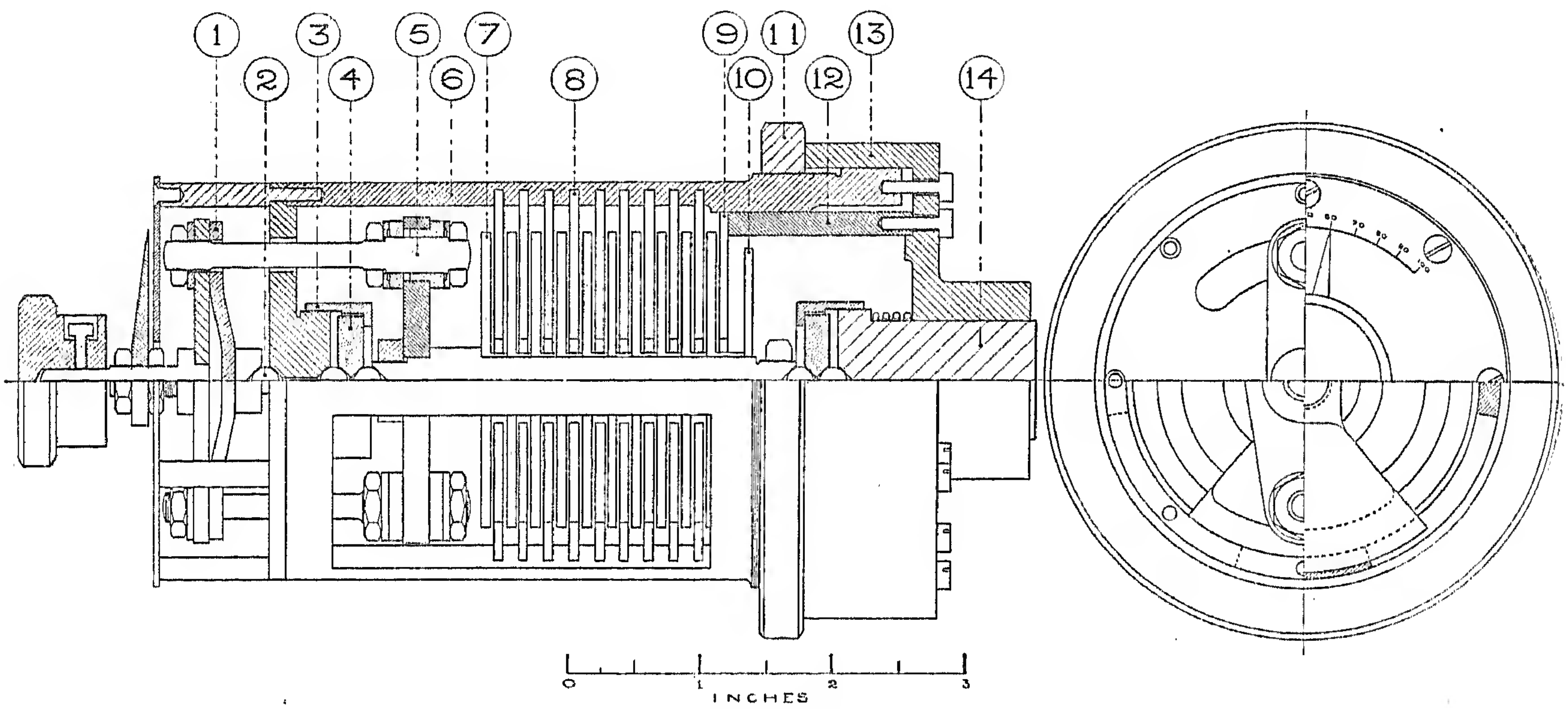


Fig. 1.—Compensated condenser No. 3.

(3) DEGREE OF COMPENSATION OBTAINED

(a) Heating Tests of Condenser

The condenser was set up in the improved oven-equipment recently installed for testing circuit components. Preliminary tests were made to ascertain the range of the coefficient of capacitance obtainable by varying the compensating adjustment. It was found that any desired temperature coefficient between + 80 and − 80 parts in a million per deg. C. could be obtained. Since the condenser was intended for use in conjunction with a coil having a temperature coefficient of inductance of between + 5 and + 10 parts in a million, the compensating ring was adjusted to give a negative capacitance-coefficient of about the same value.

The compensation having been adjusted by these preliminary trials, extensive tests were undertaken to ascertain the electrical performance of the condenser under varying conditions of temperature-change. The nature of the capacitance-variations can best be illustrated by reference to Figs. 2 and 3, depicting the changes which occurred for fast and slow heating conditions respectively, the capacitance being 170 $\mu\mu$F. In the fast heating condition the temperature-rise was about 10 deg. C. per minute, and it is seen from the lower curve of Fig. 2 that the maximum transient change of capacitance was less than 3 times the final change. The capacitance coefficient for this heating condition was $-7 \cdot 8$ parts in a million per deg. C., the maintained temperature-rise being 28 deg. C. For slow heating, at a rate of about $0 \cdot 2$ deg. C. per minute, the maximum transient change of capacitance, shown in the lower curve of Fig. 3, was about 50 per cent greater than the final change, and the capacitance coefficient for this heating condition was $- 5 \cdot 6$ parts in a million per deg. C.

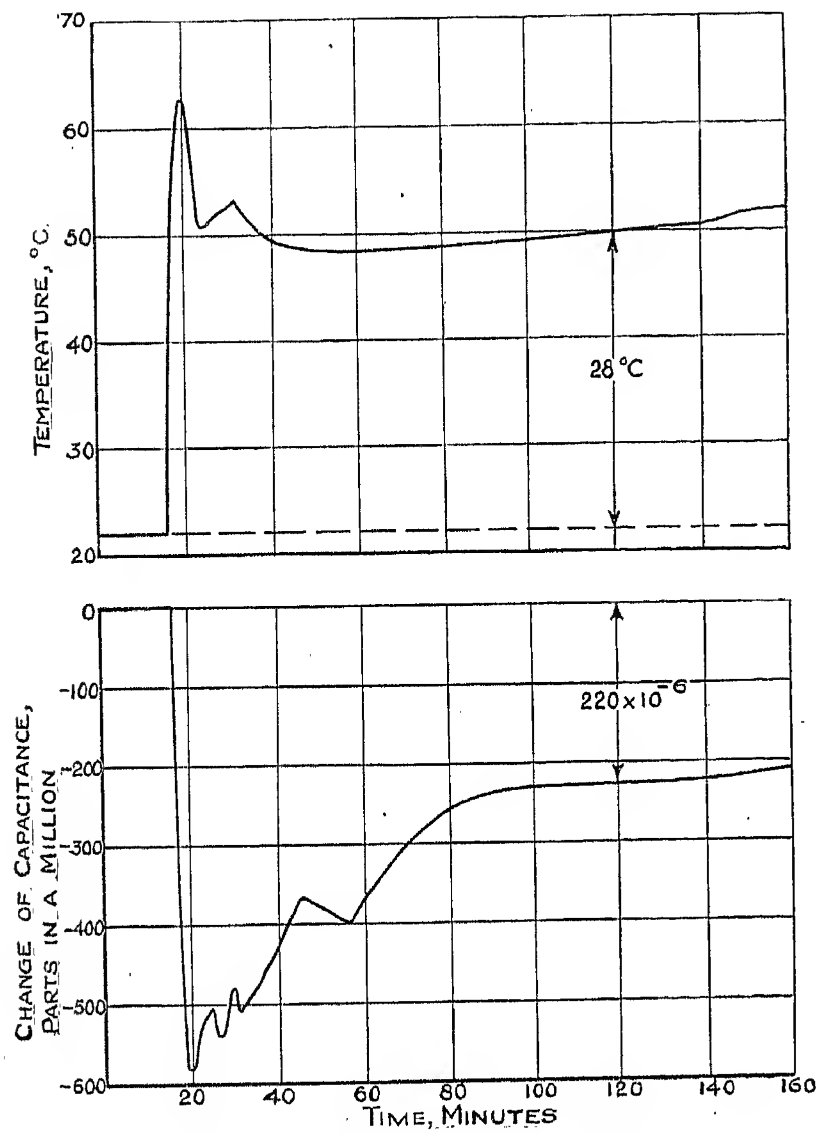


Fig. 2.—Example of rapid heating.

If these results are compared with the measurements on condenser No. 2 referred to in the previous paper,* it will be seen that the ratio of the transient to the final change of capacitance has been reduced from 15 in the case of condenser No. 2 to 2 in the present case, for the same negative temperature-coefficient. It appears, therefore, that a considerable degree of matching has been achieved between the thermal properties of the independent masses of the assembly. The residual imperfections in this respect are no doubt due to the difficulty

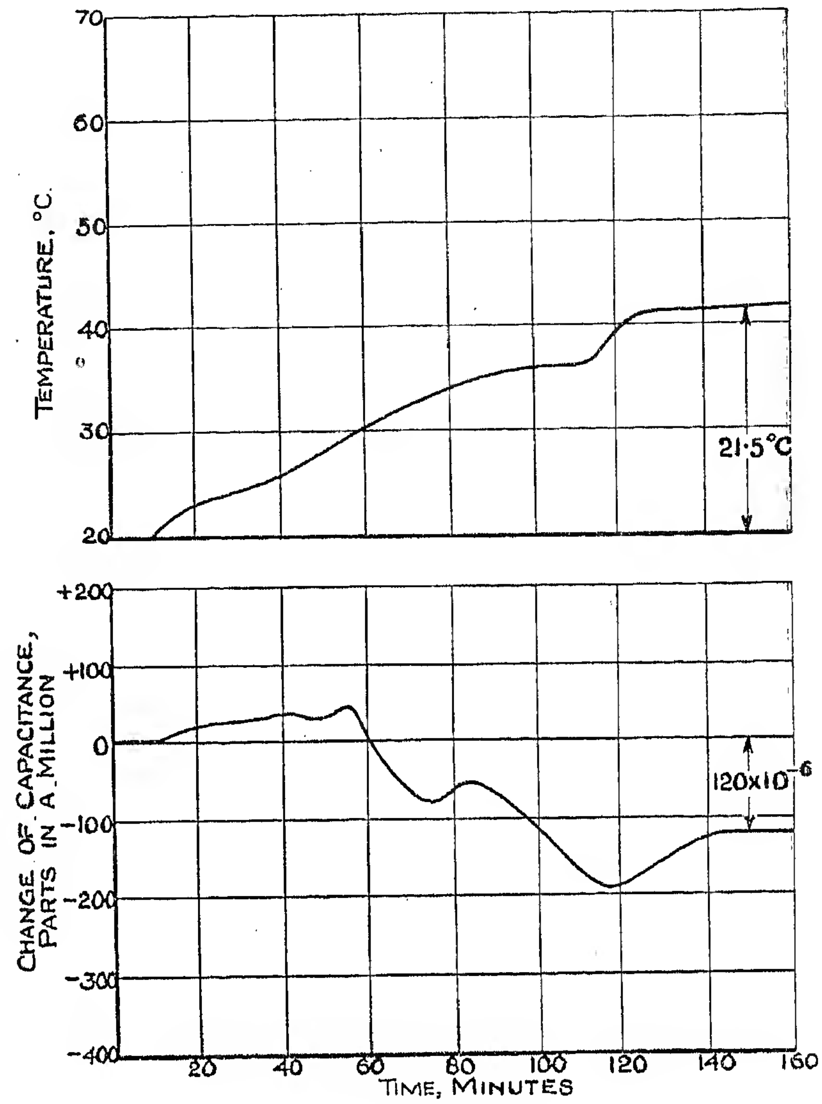


Fig. 3.—Example of slow heating.

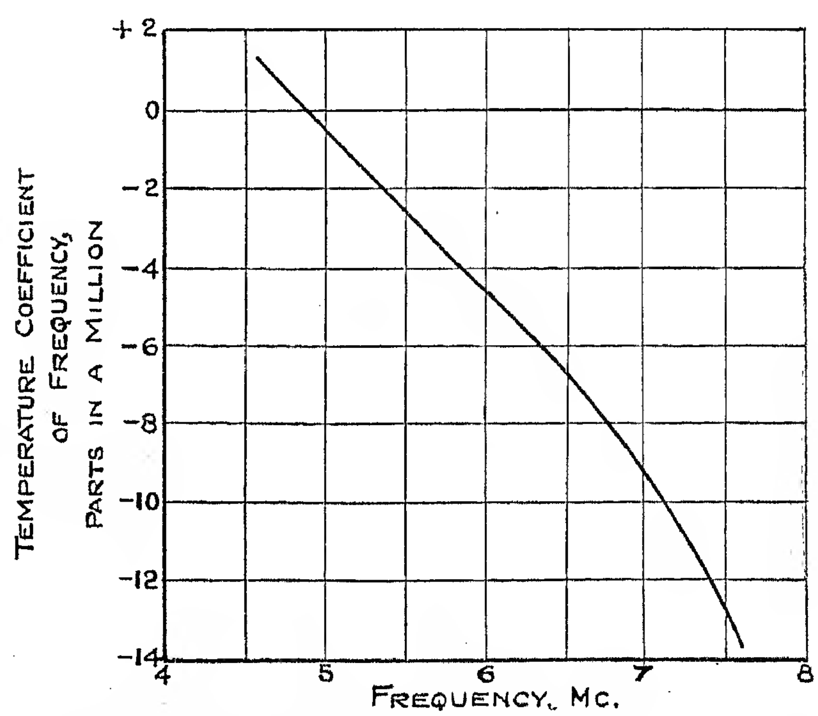


Fig. 4.—Variation of frequency coefficient of oscillation circuit with frequency.

of maintaining a good thermal contact between the steel tube (12) and the brass housing (13), although every reasonable precaution has been taken to ensure such

* *Loc. cit.*, p. 330.

thermal contact by careful grinding of this telescopic system. The curves submitted in Figs. 2 and 3 are fairly representative of other results obtained under different conditions.

Table

Capacitance	Frequency of measurement	Temperature coefficient of capacitance, parts in a million per deg. C.	
		Fast heating	Slow heating
$\mu\mu$F	kc.		
265	1 124	− 8·8	− 4·4
170	1 365	− 7·8	− 5·6
80	1 880	− 3·0	− 4·2

Measurements were made of the coefficients of capacitance given by fast and slow heating for other settings of the condenser, and the mean values obtained are shown in the Table.

It is concluded from these results that the coefficient is not appreciably dependent on the position of the rotor vanes. The design is such that this result was anticipated.

(b) Heating Tests of Complete Oscillator

The condenser was connected to an inductance to form a closed circuit, in which oscillations were maintained by a valve system. The inductance used for this purpose has been described previously.* It consists of 8 turns of tinned copper wire 0·064 in. diameter, wound on to a grooved silica former, the wire being heated and under tension during the winding process and then allowed to contract into the grooves. The magnitude of the inductance and its temperature coefficient were 4·4 μH and + 7 parts in a million per deg. C. respectively. The condenser was set at its maximum value of 265 $\mu\mu$F, the frequency of the complete circuit being 4 659 kc.

Preliminary heating tests were made and the compensation adjusted to give a small temperature coefficient of frequency. After this adjustment, no further alterations were made. Observations were taken of the frequency coefficient of the circuit for various values of the condenser setting, corresponding to various frequencies of oscillation. The results are shown in Fig. 4. At the original maximum condenser setting, the temperature coefficient of frequency was found to be about 1 part in a million per deg. C., and this coefficient varied continuously with frequency until, at 7·5 Mc., its magnitude was −13 parts in a million per deg. C. The form of this characteristic is due to the increase with frequency of the temperature coefficient of inductance of the former-wound coil, since it has been shown from observations on the capacitance coefficient of the condenser that no appreciable change in this coefficient occurs with condenser setting. Previous work on such coils has shown that the positive inductance coefficient increases with frequency.

A temperature-compensated condenser is normally required for use in a circuit covering a small frequency band, and it can be seen from Fig. 4 that over a band width of 20 per cent of the nominal frequency the change of temperature coefficient is about 4 parts in a million. Thus, if the compensation were set perfectly at a frequency f, the coefficients at frequencies of $0 \cdot 9f$ and $1 \cdot 1f$ would be about +2 and −2 parts in a million per deg. C. respectively. Such a degree of compensation is adequate for most practical purposes.

The stability of the circuit under varying conditions of temperature-change can best be illustrated by means of the results obtained over a period of six consecutive days. Referring to Fig. 5, it will be seen that in this period there were two rapid heatings and two slow heat-

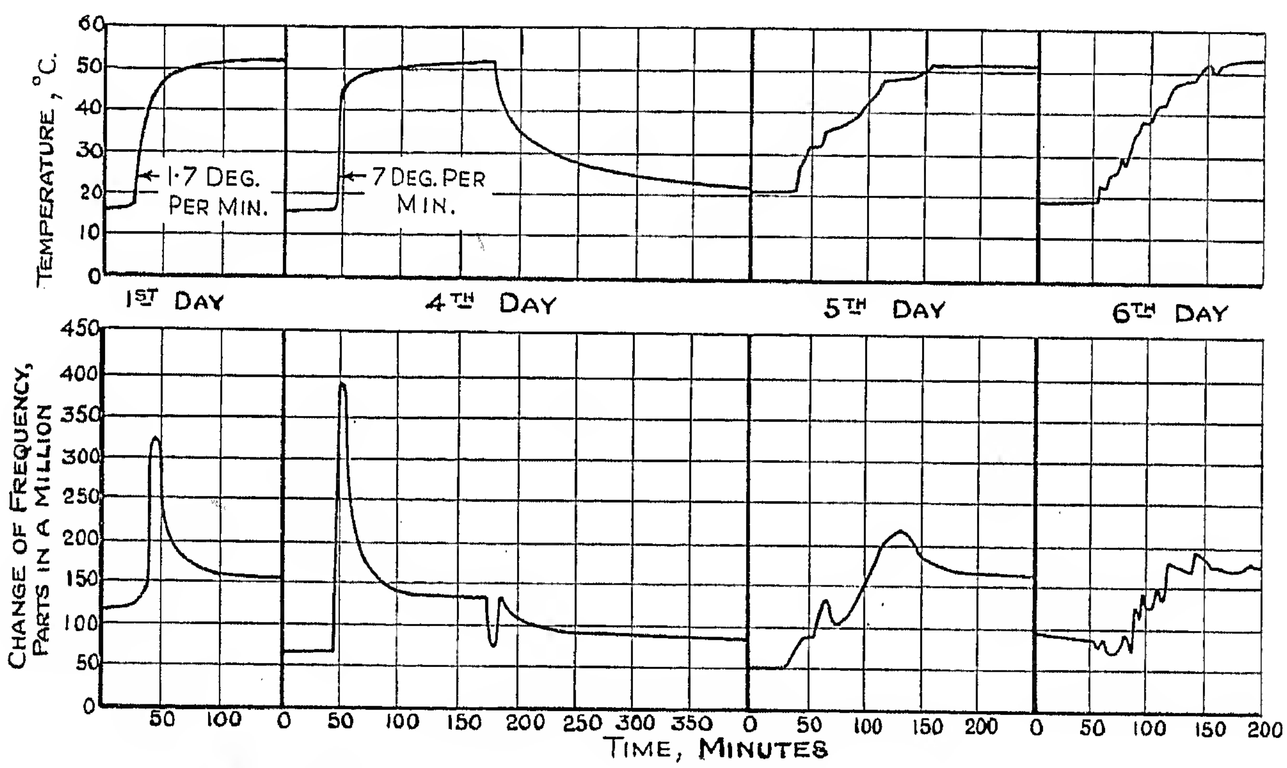


Fig. 5.—Tests of oscillation circuit with temperature variations.

* H. A. THOMAS: "The Stability of Inductance Coils for Radio Frequencies," *Journal I.E.E.*, 1935, vol. 77, p. 702 (see Coil F, page 708).

ings. The frequency of oscillation would have varied by less than 70 parts in a million over the period if normal atmospheric changes only had occurred. The frequency change due to a slow temperature-change of 30 deg. C. has a maximum value of about 150 parts in a million, and for temperature-changes at rates of about 7 degrees per minute the transient frequency aberrations do not exceed 350 parts in a million.

(4) CONCLUSION

If these results are compared with those obtained for previous compensated circuits, it will be found that a considerable improvement in temperature compensation has been made. For instance, the frequency-changes using condenser No. 2* and a good coil were of the order of 2 000 parts in a million for a rapid temperature-change of 30 deg. C., whereas for the present condenser the variation of frequency for the same thermal cycle is only 350 parts in a million, corresponding to a transient frequency-change of about 10 parts in a million per deg. C. The electrical stability of the condenser over long periods appears to be quite good, and the temperature coefficient of capacitance is almost independent of the setting of the condenser. The use of an insulated rotor enables this result to be achieved in a smaller volume than would be needed with a conventional screening case.

* *Journal I.E.E.*, 1936, vol. 79, p. 330.

When used with a coil having a positive temperature coefficient of inductance, it is possible to obtain a frequency coefficient for the circuit which is only a few parts in a million over a reasonable frequency band. For example, in the case of the circuit described previously, the frequency coefficient for slow rates of heating was about 3 parts in a million per deg. C., and for rapid changes of temperature was about 2 parts in a million. This excludes transient changes which take place during the initial heating period. It is likely that the weight of the present condenser could be reduced appreciably without seriously altering the electrical performance. If this were done, such a condenser would be suitable for most purposes where compensation is required in apparatus of small weight and size.

The stability of frequency obtainable by using such a condenser in combination with a good former-wound coil would seem to be sufficient for most present purposes.

ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scientific and Industrial Research. The author is indebted to Mr. C. W. Spencer for assistance in the experimental work, and to Mr. A. Gridley for his care in constructing the compensated condenser.

DISCUSSION ON
"THE JOINTING AND TERMINATING OF HIGH-VOLTAGE CABLES" *

NORTH-EASTERN CENTRE, AT NEWCASTLE, 8TH MARCH, 1937.

Mr. J. Haywood: Jointing generally is a matter of paramount importance, and I agree that it is not advisable to tire a jointer. To help in this direction it is possible to make one man responsible for the interior of the joint and another for the outside work; this will lessen individual work and obviate divided responsibility.

The method of making braid joints has been a matter of argument for many years. In my opinion the braid joint should be wedge-shaped, the binding starting from the conductor from one side. If the braid is wedge-shaped at the ends, rather than tapered, one can always get a good tight joint: to bind as suggested by the author makes for a loose bulky mass in the centre of the joint, which I think very undesirable.

The question of wrapping cotton tape around the core is again a matter of personal opinion. We employ two layers of impregnated cotton tape, which are perhaps not necessary. The same degree of safety can be otherwise obtained without actually removing two layers of paper from the core and risking a jointer cutting more than two layers. I think it is very dangerous for the jointer to have to use a knife in this manner. The idea of putting two layers of cotton tape on is to provide better protection. Whilst on this subject I would mention that Fig. 1 shows no support under the core, and taking the belt off the cable and removing an additional two layers of paper does not seem satisfactory.

I do not know why the author suggests using cold compound. If the compound is cold it is impossible to handle it or to make a good joint with it; a joint made with cold compound would no doubt trap appreciable quantities of air. I should prefer the use of hot compound.

The author asks for opinions on the respective merits of pot and stick wiping: I think pot wiping preferable, but in any case the result depends on the skill of the jointer.

We have had some experience of the use of styrene and have found it very satisfactory. I should like to know, however, whether the author can give any more information on this matter.

Regarding joint filling under vacuum, how far can one expect the effect of vacuum applied to the joint sleeve to extend down the cable?

Has the author had any experience of a barrier joint being opened out after, say, 5 years' service, and, if so, has any sign been evident of tracking along the surface of the porcelain?

The values given in the paper for clearances under compound appear to be based on cable research. Are they safe for the surges liable to occur on power-supply systems?

We have never been able to get cable oil to stand up to some specifications; it would appear that a definite specification for cable oils is called for. The author refers to the testing of insulation for moisture. Has he ever tried "bulldog" type tapes? By using these in the manner suggested it is possible to get rather peculiar results.

Referring to terminal boxes, Fig. 12 shows that the mass of metal is earthed through the threads of the set screws; is this advisable?

Does the author not think it advisable to elevate the core from the bottom of the sleeve shown in Fig. 10?

Mr. R. D. Spurr: The skill of the jointer is undoubtedly a factor of major importance; I have always found jointers to be conscientious workmen who consider themselves badly compromised should one of their joints fail.

Owing to the more general use of higher voltages, 6·6-kV and 11-kV joints have not received the amount of care they deserve, and many failures of such joints can be attributed to undue familiarity with these voltages.

I am of the opinion that it is safer to connect the cores colour to colour rather than to mix the colours, though it means a longer sleeve. A careful jointer will straighten out the cores to get the correct phase sequence, without leaving a source of weakness in the joint.

Until recently it was our practice to fill the lead sleeve with bituminous compound, but we now use a semi-liquid compound of the same class as that used for impregnating the paper.

We prefer lead sleeves to any kind of cast-iron box, especially where there is danger of subsidence. We are now substituting lead sleeves for a patent low-voltage tee box at every opportunity. In making tee branches with a lead sleeve under conditions where subsidence may occur a running joint is preferable, as the pull will then equally affect the branch and the main cable. In all cases joints are buried in a length of cast-iron troughing filled with bitumen and protected by cast-iron lids. We formerly had several expansion joints on 5-kV cables, but found that subsidence occurred at points in between the joints. We have since discarded these joints, and now rely entirely on lead sleeves.

Mr. L. A. Bates: With reference to the joint-operation record on page 517 relating to 33-kV belted cable, it would be interesting to know the cause of the joint failures and in what manner the design of the joint was modified for future work.

In regard to the conductor joint, does the author consider that the ferrule joint is superior either elec-

* Paper by Mr. W. Holttum (see vol. 80, p. 517).

trically or mechanically to the braided joint? Some mention of the cross-section of the ferrule or braids might be made; I assume this should be at least equal to the conductor section.

The author advocates (page 521) the use of cotton tape in preference to paper for voltages up to 22 kV, on the grounds that it is easier to apply by reason of its greater mechanical strength. In view of the much greater electric strength of paper tape I assume that a considerably smaller thickness of this type of insulation would be required, which would compensate to some extent for the fact that it is more difficult to apply and would also effect a welcome reduction in the dimensions of the joint sleeve.

The use of cotton tape next to the conductor for filling in the end spaces up to the diameter of the ferrule on joints for voltages above 22 kV does not appear to be good practice. One would expect that a material with an electric strength at least as good as that of the remainder of the joint insulation would be used at a point where the maximum stress probably occurs. I believe that impregnated silk has been used, and I should be glad of any details of the properties of silk tape compared with those of paper and cotton.

Referring to Fig. 7, will the author explain why stress cones are not shown on the single-core side of the joint?

In regard to "vacuum and pressure" filling (page 530), I would suggest that more attention might be paid to the provision of suitable nipples on the joint sleeve to enable the leads from the vacuum pump and compound reservoir to be positively connected to the sleeve.

In regard to 66-kV sealing ends, our experience has been that it is advisable to provide an auxiliary reservoir external to the bell to maintain the pressure of the compound above atmospheric and so prevent ingress of moisture. This arrangement has been in use for nearly 7 years in this area, and so far no failures have occurred.

Referring to the specification for insulating oils on page 541, should not the duration of the test also be specified? My experience has been that even very high-grade insulating oils will not withstand the voltage specified for any appreciable period.

The author refers on page 530 to the styrene joint. To me, this joint is particularly interesting; the joint sleeve is only slightly larger than the cable sheath, and it may be of interest to mention that it occupies only about one-fifteenth of the space of the 66-kV joint shown in Fig. 4. A number of these joints have been installed in this area and have been operating at 66 kV for nearly 3 years. The styrene joint is such a radical departure from previously accepted practice that one hopes it will prove successful, or at any rate help in some way towards achieving some improvement in joint design.

Mr. E. C. I. Macdonald: The importance of reducing to a minimum the human element and the consequent possibility of introducing weaknesses in high-voltage cable systems is one which concerns both the user and the cable manufacturer. It appears that development of joints such as that employing styrene, as described on page 530, is likely to afford valuable results.

On page 531 the author suggests that the cable sheaths of a large system themselves form a good earth, and I agree that cable sheaths are usually securely earthed at the ends of the route. I would point out that a usual specification for armoured and waterproofed cables includes over the lead sheath two impregnated paper tapes, one impregnated cotton tape, and one hessian tape. If armouring wires are used they are laid over the above covers and themselves covered with two further impregnated hessian tapes, the whole cable then being thickly coated with compound. Such a cable finish has a comparatively high insulation resistance and by its nature is designed to last a number of years in good condition. The use of auxiliary earths by the C.E.B. does not, therefore, appear so unjustified as the author seems to suggest.

In connection with the future developments referred to on page 540, can the author give any information as to the voltage up to which the moulding powders are used and also the temperature to which it is necessary to raise the powder for moulding purposes? The latter is presumably sufficiently low to avoid any risk of damage to the paper insulation and yet high enough not to introduce risks of softening of the moulded case due to the maximum temperature which the cable may attain in service.

Mr. W. N. Waggott: An interesting design feature illustrated in the drawings of cable joints and terminations included in the paper is the use of rubber for the making of oiltight joints. Several makes of oil- and temperature-resisting rubber are now available and this material is coming more and more into general use for the making of joints in electrical equipment of the oil- and compound-filled type, including cable boxes, switchgear, and apparatus such as transformers where the normal temperature of the oil may be of the order of 90° C. Rubber-packed joints are simple to make, they do not call for machined joint faces and, an equally important point, they are easy to break and remake.

I support Mr. Haywood in questioning the dimensions quoted in Table 3 for safe clearances between phases through compound. I consider the dimensions recommended by the author rather meagre.

Dealing with the earthing of cable sheaths, the author recommends that feeders consisting of three single-core cables should have the sheaths bonded and earthed at each end of a run at the point where they separate, and insulated at the terminations. He goes on to state that earthing the sheaths at the terminations would result in increased sheath currents, which for short lengths of large-section cable would cause serious heating. I agree with the author that serious heating would occur if the sheaths were earthed at both terminations, but I consider that satisfactory results can be obtained in the majority of cases by earthing the sheaths at one termination and insulating them throughout the route and at the other end. I should like to have the author's opinion on this point. Reference to Fig. 15 suggests that the author has had experience of this method of earthing the sheath at one end only, as the sealing end shown in this figure has provision for earthing the cable sheath by means of a copper strip short-circuiting the insulation.

Mr. C. Turnbull: The problem of earthing is mentioned in the paper. Two conditions are usually con-

sidered sufficient to ensure a satisfactory earth: (1) good contact with the earth, (2) that if two earth plates are in use the resistance between them should be low. Neither of these conditions, however, is enough. Cases have been known where a street has become alive in consequence of a cable fault, and horses have received shocks from the ground. The contact with earth was good, but there was not enough conductivity to dissipate the current. If two earth plates are sunk in the ground and connected by a piece of thin copper wire they will give a low resistance test between them, but a rush of current may not be properly dissipated. I feel that the ultimate way to deal with earthing will be to lay a continuous separate earthing cable in contact with the earth wherever there are cables, this being connected at intervals with good earth plates. Such an earthing system would give adequate protection even in a district where the soil generally had poor conductivity.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, LIVERPOOL, AND NEWCASTLE*

Mr. W. Holttum *(in reply)* :

London

In reply to Mr. Siviour's first comment, if he refers to the connecting of cables into transformer and switchgear chambers this was not regarded as being within the scope of the paper. Alternatively, the making of joints on cables with heavy conductors does not involve any special features.

The word "normal" is used to indicate a joint of the simplest and most usual type, i.e. the type which is normally used. The word "straight," which Mr. Siviour seems to prefer, might equally be applied to an expansion or barrier joint. My only objection to the term "dividing box" is that it is frequently used to describe a terminal box, and "trifurcating joint" avoids this ambiguity. A definite ruling is required, and there is perhaps room for a new term such as "separating joint," leaving the term "dividing box" to be used for S.L. cable.

With regard to the time taken in making repairs, existing designs result from considerations of reliability and economy. If speed of jointing were to be a controlling factor designs might be modified to that end, and the buyer should frame his enquiries accordingly. In most cases, however, the actual time of jointing is a smaller proportion of the total repair time than in the case mentioned by Mr. Siviour.

The reinforced lead sleeve is a quite simple construction, and its advantage over an iron sleeve with machined joints is that it is cheaper and more reliably watertight.

With regard to the replenishment of the cable beneath the wipe, while this would probably take place from the adjoining cable it might take a long time, particularly if the cable remained unheated; feeding from the joint would be much quicker, but is of course incompatible with the prevention of migration.

The voltages in Table 1 are meant for ordinarily clean conditions, and the British Standard Specification from which they are taken provides for the use of a higher-rated insulator where necessary.

The box in Fig. 12 is meant for fluid compound filling, so that a plumbed wipe is necessary, but for Fig. 13 hard-setting compound is used and the split-lead-cone construction could be employed.

Replying to Mr. Scott, I am afraid there is some difference in conception of what is meant by "main principles." For my discussion of them I would refer him to the first two paragraphs on page 518, commencing on page 517. Regarding my attitude to any such principles, seeing that they are unavoidable the only possible attitude would appear to be to accept them and endeavour to apply them as economically as possible. I am obliged for Mr. Scott's compliance with my request for a statement regarding principles according to his view, given at the end of his contribution, though he states what his principles should be based on rather than what they are. No one could object to Mr. Scott's items (*a*), (*b*), and (*c*), but there may be differences of opinion as to whether (*b*) and (*c*) are even remotely possible, and whether the application of (*a*) would not do more harm than good. In fact I had assumed it to be generally admitted that the disadvantages of the solid type of cable implied in (*b*) could only be completely avoided by using cable of another type.

No performance figures have been given for the reason that the statement that joints and terminations can be made of equivalent strength to the cable is regarded as sufficient. This implies that the cable system is not weakened by the inclusion of joints, although it may be admitted that if there is a large number of joints it is possible that some fortuitous or transient condition will provide a joint weaker than the cable. No standard of cable performance is specified, and if the cable standard is raised there should be no difficulty in applying the present principles of design and developing the present methods of construction to meet the situation. As Mr. Scott implies, some of the designs illustrated in the paper have proved equal to the needs of 7 years or more, although minor improvements have been introduced during that period.

I agree that for cables with the present types of compound there is something to be said for making every joint a barrier. At present, however, the cost does not appear to be justified and a better solution would be to find a kind of cable compound which made barriers unnecessary.

Mr. Scott's reference to the absorption of moisture from compound by the fibres of paper is interesting, but I am unaware of any evidence that it is of practical importance, and the methods of drying and testing for dryness referred to in the paper are found satisfactory.

I am not aware of any evidence that compound as used for joint filling can be harmful to the cable through migration, and would suggest that the faults referred to by Mr. Scott in regions adjacent to joints are due to the nature of the compound used rather than to its condition. The possibility of eliminating the air cushion must depend

* The London and Liverpool discussions will be found in Volume 80, pages 543 and 547 respectively, and the Newcastle discussion in Volume 81, page 282.

upon first finding some way to avoid or render innocuous the low pressures which would result. The use of sylphon or pressure reservoirs would court the danger of bursting the cable sheath by excessive absorption of compound.

I am interested to note Mr. Webb's statement that there is evidence that barrier joints have saved trouble. The styrene joint would appear to provide a very convenient form of barrier, but if the external reservoir referred to in the patent is necessary to provide against migration on the lower side of such joints it will very greatly offset this convenience. Regarding the treatment of cable ends with styrene to prevent percolation of the transformer oil, my opinion is that cable-terminating chambers on transformers should be so designed that the transformer oil cannot gain access.

The use of condenser cones reduces the necessary length of exposed cable insulation, but the length of the cone extending over the cable sheath offsets this advantage, and the economy referred to by Mr. Webb is not apparent. The types of stress cones used in the paper are found satisfactory and are quite inexpensive. Admittedly any paper tube used for the stress cones must grip the cable closely, and there is no difficulty in accomplishing this, particularly if the cable is straightened before the sheath is removed.

The reduction of the breakdown value of a 33-kV joint to 2 kV under vacuum would appear to imply considerable occlusion of air. It is not apparent what advantage there would be in testing under vacuum, which can only illustrate a fortuitous and variable condition.

The reason for preferring a 2-mm. gap for oil or compound testing is that a lower voltage is required than for a 4-mm. gap, and the repeat tests which it is usual to carry out on one sample produce much less carbonization.

I am interested in Mr. Urmston's reference to stress cones, but while the design of these provides scope for mathematical theory my opinion is that anything gained by the refinements of theoretical design comes well within the limits of normal variation in practice and is therefore not of practical importance.

I am acquainted with the patent of Dr. Brazier's stress cone integral with the cable end, and await with interest the practical application of this, which would appear to be a matter of some difficulty.

In reply to the question whether a cable or its joints should be the electrically stronger, while the former would provide the advantage that faults would be limited to joints and location would therefore be simplified, it seems to me that economics clearly dictates that the two should be as nearly equal in strength as possible.

It is difficult for me to say anything relevant to Mr. Jockel's first point as he does not give any details of the mechanical failure of sleeves. Regarding the bleeding of terminations, drained cables can be supplied up to 11 kV, but if an indoor box is used and there is a tendency for compound to migrate into it then it should be of oiltight design. Other alternatives which may in some cases be effective are the use of oil-resisting compound, or taping the exposed cable cores with oil-resisting tape.

With regard to the testing of cables after installation, the use of direct current or alternating current is determined by practical considerations, and while an a.c. test is more searching it is impracticable for long feeders, although it is most convenient for single lengths in the factory.

The hydrostatic testing of cable sheaths is not found to be practicable, and reliance must be placed upon satisfactory lead covering.

In reply to Dr. Dunsheath and Mr. Bolton, I would suggest filling up joints installed in such a way with compound of higher viscosity than usual, and leaving an increased air space. The large variation of pressure referred to by Mr. Bolton suggests that the air space was insufficient. Sealing ends with parallel glass insulators for outdoor use up to 11 kV can be supplied, but shedded glass insulators for cable terminations have not, so far as I am aware, been developed.

Liverpool

In reply to Mr. Davey's comments on Fig. 5, while the use of silk tape as suggested might give added rigidity, the mass of paper taping is found satisfactory without it, and the high dielectric loss of the silk makes it undesirable. The conducting tape referred to for screening is presumably extensible and would be convenient, provided the conducting surface was not broken by application.

Fig. 7 was inserted particularly to illustrate the type of sleeve shown, and this joint would now be installed with stress cones at both the single-core and the 3-core ends.

Regarding testing at atmospheric pressure, any attempt to represent service conditions must in my opinion give a fortuitous result. The maintenance of a specified degree of vacuum would be a sounder proposition, but I consider that atmospheric pressure provides an equally good basis of comparison. I am interested in Mr. Davey's remarks on the analytical testing of joints, and the method referred to provides a means of assessing the relative strength of the various parts. On the other hand, if the power factor is measured on a joint as a whole the weakest place can be found by dissecting it after the power factor has risen, and disturbance of the normal construction is thus avoided.

In reply to Mr. Milner, the pouring temperature for oil-resin compound is not critical, nor are the lower and upper limits of the permissible range, which are determined by viscosity and deterioration respectively. A suitable temperature is 200° F., and the compound should not be kept at this temperature longer than necessary.

The flashover distance along porcelain under compound at atmospheric pressure is of the order of 75 % in excess of the dry flashover in air. The design shown by Fig. 12 is found satisfactory in all respects. In the indoor terminal box in Fig. 13 the strand is sweated solid to below the compound level, and this, with the hard-setting compound, gives sufficient protection against moisture for an indoor box.

The moulded insulation under the stress cone in Fig. 16(*e*) has a permittivity more than twice that of the impregnated paper. The effect of this is to keep up the radial stress in the cable insulation in the region influenced by the stress cone through the deflection of the equipotential lines towards the conductor, with the result that the longitudinal stress is reduced by being distributed over a great length.

In reply to Mr. Pirie, the relation between the possible strength of a joint and of the cable depends upon the

cable at the end of the sheath, which is to be regarded as part of the joint. The better compounding here may possibly more than compensate for the worse conditions of stress. The electric strength in the region of the conductor joint is, of course, only limited by the dimensions.

The top of the stress cone in the sealing-end insulator in Fig. 15 is made level with the external metal ring. If it were lower the stress conditions on the cable end would be improved, but there would be increased stress externally at the top of the metal ring. The position shown is considered to be the best.

Regarding the relative expansion of conductor and sheath, it is found that for long lengths of cable there is no tendency to relative movement except at the extreme ends, and the tendency there is insufficient to warrant special provision. In addition, as stated in the paper, the conductor is relatively inextensible compared with the sheath, and expansion joints are recommended to deal with subsidence effects only and not for thermal expansion.

Impulse and high-frequency testing will no doubt be standardized in due course, but are not likely to be a substitute for a test at working frequency. The difficulty of an ideal specification for the latter is referred to in the paper.

In reply to Mr. Waygood, the percentage cost of joints varies widely with the voltage and also with the conductor size, which has a large effect on the cost of the cable but little effect on the joint. Roughly, the cost of joints supplied and fixed as a percentage of the cost of joints plus cable, including laying but excluding cost of excavation, and assuming joints spaced at 220 yards, may be taken to vary from 4 for the lower voltages to 12 for the highest.

Newcastle

In reply to Mr. Haywood's remarks regarding the method of making braid joints, the braids should be tapered on one side only, the cut side being laid against the conductor. The braid is sufficiently stiff not to bunch up in the centre when bound from the ends.

I agree with Mr. Haywood that to use a knife in removing two layers of paper would be dangerous. A knife should only be used when cutting through a considerable thickness, and the last few layers should be torn.

In the joint shown in Fig. 1 it is not found that there is any need to support the cores between the conductor joint and the sheath. In Fig. 10 bands of tape are shown to separate the cores from each other and from the sleeve, and can be increased in thickness where this seems necessary.

The use of cold compound is only recommended in connection with taping, and its advantages are indicated by the reasons given in the paper against basting.

The vacuum applied during vacuum filling would probably penetrate only a short distance along the cable. The only data I have are from one test in which it was found that, when a high vacuum was applied to a piece of 66-kV single-core cable, in 4 hours a reading of 6 in. was reached on a vacuum gauge connected to the sheath at a point 5 ft. away, the temperature being 60° F.

I have no knowledge of tracking having been found on the porcelain of barrier joints opened up either for examination or as a result of a fault. A few joints have been examined after operating periods up to 6 years.

The values given for clearances under compound are based on experience, but the uncertain value of surges under modern conditions may possibly suggest revision. I have no reason to think, however, that the values given are inadequate.

The moisture tests referred to in the paper are for the kinds of insulation used in high-voltage joints, and I have no data in regard to the reaction of bulldog tapes.

Regarding the earthing of the terminal box in Fig. 12 through the studs holding the gland, the primary purpose of the earth lead is to earth the cable, and the studs are an adequate connection for the box, and will bear comparison with the earth-lead attachment.

In reply to Mr. Spurr, if colour-to-colour jointing is wanted a longer sleeve is required, but I am not aware of any general demand for such jointing.

In reply to Mr. Bates, the 17 joint failures on belted cable occurred with joints in cast-iron sleeves, and in 9 cases the sleeve was found fractured. The failures were probably due to migration of compound or ingress of moisture. In 7 other cases moisture was considered to be the cause, and in the remaining case migration of compound. Modern sleeves are more reliably watertight, and owing to the use of better-impregnated cable there is less tendency for migration.

I consider that the ferrule joint is superior electrically to the braid joint, as there is less risk of leaving harmful points. It is usual, as suggested, to make the cross-section of the jointing members not less than that of the cable conductor.

In regard to the use of impregnated cotton tape, no additional bulk is required over the use of paper for 22-kV joints with paper-tube insulation, as in either case sufficient tape is put on to fill the tube, the size of which is not affected. The conductor joint is in the position of minimum stress on account of the increased spacing, and 66-kV single-core joints in which all the tape used was of cotton have been found satisfactory. I have no exact information as to the properties of silk tape, but have no reason to suppose it is better than cotton; further, it has the disadvantage of being non-porous.

The absence of stress cones in Fig. 7 is referred to in the reply to the Liverpool discussion.

The connections to the joint for vacuum and pressure filling are made by tapered rubber-sleeved tubes thrust into tapered nozzles, the junction being kept immersed in compound by filling the annular depression in the top of the nozzles. This gives a perfectly vacuum-tight connection, and is easily made pressure-tight by tying the fitting down to the sleeve. I am not aware of any form of screwed connection which would not be more expensive and less satisfactory, and more difficult to seal permanently.

The duration of the voltage test on insulating oils is not important as if the oil is free from air a voltage slightly below the breakdown value will be held for a long time. It is, however, desirable for practical work to stipulate a time, and 1 minute is suitable.

In reply to Mr. Macdonald, the insulation of joints by means of moulding powders has not advanced sufficiently for it to be possible to specify the limit of

voltage to which it is applicable, but I know of no reason why it should not be suitable for the highest voltages. The temperature at which the powder can be applied is in the region of 180° C., and for the short period required will not damage the cable insulation.

I am pleased to note that Mr. Waggott advocates the use of oil-resisting rubber, but would recommend that machined jointing faces should be used where perfect sealing is vital.

Short runs of three single-core cables may be laid, as Mr. Waggott suggests, with the sheaths bonded and earthed at one end only; the limitation of this arrangement occurs when the voltage-rise at the insulated end of the sheaths exceeds the danger limit. As this might occur under fault conditions for comparatively short lengths, bonding at both ends at the point where the cables separate is generally preferable, but the sheaths may be left open-circuited under suitable conditions. Regarding Fig. 15, it is usual to provide means for short-circuiting insulated glands if required.

In reply to Mr. Turnbull, while his proposal of an earthed cable is no doubt ideal, a very dense system of cables would appear to be necessary to make it worth while.

INSTITUTION NOTES

VERBAND DEUTSCHER ELEKTROTECHNIKER

At the request of the above society the Council have agreed to the mutual granting of facilities and privileges as Visiting Members to members of the two societies visiting each other's country.

Members who intend to visit Germany and wish to avail themselves of this arrangement should apply to the Secretary of The Institution for a letter of introduction to the Verband Deutscher Elektrotechniker, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are connected.

COOPERS HILL WAR MEMORIAL PRIZE AND MEDAL

The Secretary desires to remind members that the latest date for submitting MSS. in connection with the triennial award of the above Prize and Medal is the 1st October.

The papers must be specially written for the purpose of the competition, which is restricted to Corporate Members of The Institution who were under 35 years of age on the 1st January, 1937. Competitors are invited to submit a paper on any subject coming within the scope of electrical science or electrical engineering and their applications. Full particulars can be obtained on application to the Secretary of The Institution.

SUBSCRIPTIONS OF RETIRED MEMBERS

Members are reminded of the Rule in regard to the subscriptions of Corporate Members of long standing who have retired from the profession. The Rule reads as follows:—

"Any Corporate Member who has reached the age of 60 and has retired from the practice of his profession or business, may apply to the Council to remit his future annual subscriptions, provided that his membership of The Institution has been continuous for at least 25 years. If he desires to have the publications of The Institution he will receive them on payment of one guinea per annum."

PREMIUMS

In addition to the Premiums mentioned on pages 677 and 678 (vol. 80) of the June issue of the *Journal*, the Council have awarded the following Premiums for papers read before the Students' Sections during the session 1936–37:—

Premiums of the value of £10 *each*:

Author	*Title of Paper*	*Where read*
J. E. Houldin, B.Eng.	"The Magnetron"	Liverpool
W. E. Laycock	"Electrical Methods of determining Cable-Sheath Uniformity"	London
P. M. Newman, M.Sc.	"High-Tension Porcelain Insulators"	Birmingham

Premiums of the value of £5 *each*:

Author	*Title of Paper*	*Where read*
H. K. Bourne, B.Sc.	"Aviation Lighting and Radio Equipment"	Birmingham
W. J. Cozens	"Machinery Foundations"	Edinburgh & Glasgow
J. D. Evershed, B.Sc.	"The Manufacture of Electrical Machinery"	Birmingham
J. W. Fair	"Oil Circuit-Breakers"	Chester
G. V. Harrap	"Taxation of Electricity Undertakings"	Leeds
D. N. A. James	"Problems of Braking on Electric Railways"	Liverpool
G. Ovens, B.Sc. (Eng.)	"Paper-making Problems for the Electrical Engineer"	Birmingham
J. A. Stanfield	"Voice-Frequency Telegraphy"	Newcastle

COUNCIL FOR THE YEAR, 1937–1938

The scrutineers appointed at the Ordinary Meeting held on the 22nd April, 1937, have reported to the President that the result of the ballot to fill the vacancies which will occur on the Council on the 30th September next is as follows:—

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The Council for the year 1937–1938 will therefore be constituted as follows:—

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Together with the Chairman of the Meter and Instrument Section, the Chairman of the Transmission Section, the Chairman of the Wireless Section, and the Chairman and immediate Past-Chairman of each Local Centre.

GRADUATESHIP EXAMINATION RESULTS: MAY, 1937

Passed*

Adams, William Arthur.
Allison, Alfred John.
Andrew, James Clark.
Aspin, John James Edwin.
Bachelor, Edward Charles.
Beardsworth, Russell.
Boothman, Gerald.
Boud, Frederick Harry.

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed—*continued*

Brownjohn, Royce.
Burgess, Alfred John.
Chadwick, Allen.
Clay, George Robert.
Cundy, Patrick Frank.
Datta, Sudhindra Chandra.
Deacon, John Alfred.
Duff, Duncan.
Dunlop, Thomas Gibson.
Evans, Daniel Thomas.
Evans, Herbert Martin.
Exley, James.
Harrison, John Dennis.
Harvey, Leonard.
Hodgson, West.
Hume, John McIntosh.
Jacoby, George Arthur.
Jeffrey, Charles.
Jones, Ivor Roderick L.
King, John Arthur Clement.
Laver, Frederick John Murray.
Makin, Thomas.
Meacock, John Arthur.
Nield, Cyril.
Parnell, Albert John.
Parsons, Arthur James.
Phillips, Philip Carthew.
Phillips, William James.
Porter, Harold.
Preston, Henry Somerville.
Richardson, John Gregory.
Shashoua, Stafford.
Simpson, George Francis.
Singh, Bhagwant.
Singh, Kirpal.
Spearman, Felix Robert James.
Stenning, Luis Charles.
Tandon, Maharaj Krishna.
Taylor, Leo Vincent.
Townsend, Eric Henry.
Turk, John Thorp.
Winram, Norman.
Woffendale, Ernest Herron.
Wood, Peard Thornton.
Woods, Cecil Herbert.
Woolmer, Cyril Keefe Joseph.

Passed Part I only

Anderson, James.
Apte, Vishwanath Vinayak.
Atkinson, Arthur Ralph.
Bastin, Douglas James.
Boden, George Harry.
Coleman, Thomas William.
Collier, George Elder.
Dronnikoff, Serge Nicolas.
Dumbreck, John Stuart.
Elsheikh, Salem Soliman.
Hick, George.
Jenkins, Llewelyn Evans.
Jones, Frank.
Leach, Edward George.
Lewis, David.
Little, Henry.
Medcalf, Richard James.
Parr, Asa.
Perkins, Henry Whitworth.
Smillie, Ronald.
Smith, James Newton.
Tokmakoff, Wladimir Veniamin.
Turnbull, Peter.
Wylie, John Howard.

Passed Part II only

Barnard, Rodney George.
Crawshaw, Geoffrey.
Crumblehulme, Leslie Ashton.
Dewhurst, Frank.
Dickinson, Fred.
England, Ralph.
Gilmore, James Kenneth.
Gregory, William Herbert.
Grieve, Daniel McLay.
Habicht, Ronald Charles.
Harris, Frederick Llewellyn.
Hill, Constantine Thomas.
Jeffs, Eric Arthur.
Litchfield, Wilfred.
McLoughland, Thomas.
Meek, George Gilbert.
Moore, Frederick George.
Odell, Trevor George.
Parry, Arnold Holmes.
Raby, Charles Henry.
Threlfall, Andrew James Clifton.


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